NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

ANALYSIS OF THE NASA SHUTTLE HYPERVELOCITY IMPACT DATABASE

by

Michael S. Stucky

September 2003

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<tr><td colspan="4">REPORT DOCUMENTATION PAGE</td><td colspan="2">Form Approved OMB No. 0704-0188</td></tr>
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<tr><td colspan="2">1. AGENCY USE ONLY (Leave blank)</td><td>2. REPORT DATE
September 2003</td><td colspan="3">3. REPORT TYPE AND DATES COVERED
Master’s Thesis</td></tr>
<tr><td colspan="4">4. TITLE AND SUBTITLE: Analysis of the NASA Shuttle Hypervelocity Impact Database</td><td colspan="2" rowspan="2">5. FUNDING NUMBERS</td></tr>
<tr><td colspan="4">6. AUTHOR Michael S. Stucky</td></tr>
<tr><td colspan="4">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="4">9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A</td><td colspan="2">10. SPONSORING/MONITORING AGENCY REPORT NUMBER</td></tr>
<tr><td colspan="6">11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.</td></tr>
<tr><td colspan="4">12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.</td><td colspan="2">12b. DISTRIBUTION CODE</td></tr>
<tr><td colspan="6">13. ABSTRACT (maximum 200 words)
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In an effort to characterize and evaluate the meteoroid and orbital debris (M/OD) environment in low earth orbit, post-flight surveys of the shuttle orbiters are conducted to identify damage caused by hypervelocity impacts from M/OD. Survey analysis determines whether the impactor was a naturally occurring meteoroid or man-made orbital debris, as well as the impactor’s size and impact velocity.
From the post-flight survey data, calculations on the number of impacts from specific particle diameters or specific particle materials are made and compared to mission parameters to help engineers design spacecraft for better mission efficiency by reducing the effects of M/OD impacts.
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<tr><td colspan="5" rowspan="2">14. SUBJECT TERMS
Regression Analysis, Space Shuttle, Hypervelocity Impact, Meteoroid, Orbital Debris, Low Earth Orbit</td><td>15. NUMBER OF PAGES
93</td></tr>
<tr><td>16. PRICE CODE</td></tr>
<tr><td>17. SECURITY CLASSIFICATION OF REPORT
Unclassified</td><td colspan="2">18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified</td><td colspan="2">19. SECURITY CLASSIFICATION OF ABSTRACT
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ANALYSIS OF THE NASA SHUTTLE HYPERVELOCITY IMPACT DATABASE

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
September 2003

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ACKNOWLEDGMENTS

I would like to thank Dr. David Olwell, Senior Lecturer at the Naval Postgraduate School's Department of Operations Research in the Graduate School of Operations and Information Sciences, for teaching me everything I know about statistics. This thesis would not have been possible without his insight and support.

I would like to thank Mr. Eric Christiansen, Chief Analyst at the Johnson Space Center's Hypervelocity Impact Test Facility, for his guidance and help on this thesis. The opportunity to work on this project has been fantastic. Also Mr. Dana Lear and Mr. Jim Hyde were extremely helpful in providing insight and an understanding of the database and its composition.

Finally, I would like to thank my family, Maureen and Margaret, for their continual support, understanding, patience and encouragement during my course of study at NPS and throughout my work on this thesis. Without their support, I would not have been able to do this.

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I. BACKGROUND

A. INTRODUCTION

As part of the National Aeronautical and Space Administration's (NASA) effort to characterize and evaluate the Meteoroid and Orbital Debris (M/OD) environment in Low Earth Orbit (LEO), post-flight surveys of Space Shuttle Orbiter Vehicles are conducted to identify damage caused by hypervelocity impacts from M/OD. [Ref. 1] Damage discovered from these surveys is cataloged in the NASA Shuttle Hypervelocity Impact Database.

The database is a Microsoft Excel spreadsheet which is a record of 2,067 cataloged impacts from naturally occurring Meteoroids and man-made Orbital Debris on the shuttle orbiters as seen from 50 post-flight inspections between STS-50 in 1992, and STS-110 in 2002. Cataloging of M/OD damage did not begin until STS-50, and only periodic analysis of orbiter M/OD damage occurred after STS-50 through 1994 due to resource limitations. Comprehensive M/OD surveys began again in 1995 with STS-71, the first Mir docking mission, to monitor M/OD impact effects prior to assembly operations of the International Space Station. [Ref. 2]

Only about 10 percent of the orbiters surface area is inspected. Current practice calls for documentation of all Hypervelocity Impact (HVI) damage that occurs to Windows, Radiator Panels, Reinforced Carbon-Carbon and Flexible Reusable Surface Insulation on the outer payload bay doors. [Ref. 2] It should be pointed out that Radiator Impact data is the most true to the environment, as the radiators are only exposed while on orbit, where windows and other external surfaces can obtain damage while on the ground or in transit during launch or landing.

The objective of this paper is to apply a statistical model, called Arc, to the database to asses possible correlations between mission parameters such as inclination, altitude, duration and year, to damage inflicted upon the shuttle orbiter fleet.

B. POST-FLIGHT ORBITER INSPECTIONS

The Orbiter M/OD analysis program began with STS-50 in 1992 at the request of the Shuttle Program Manager who wanted a survey made of meteoroid and orbital debris damage after the first extended duration flight due to pre-flight interest in M/OD mission risks. [Ref. 2] As a result, part of the extensive post-flight inspection of the Space Shuttle Orbiter Vehicles at KSC is a visual inspection of the Orbiter surfaces for M/OD impacts based on damage features that are characteristic of HVI. Johnson Space Center (JSC) established protocols to receive data from KSC on damage found during the vehicle post-flight inspection, and to assist KSC in obtaining samples of the impact damage for analysis in laboratories at JSC. [Ref. 2]

Orbiter surfaces typically surveyed for hypervelocity impact damage are the radiators, windows, flexible reusable surface insulation (FRSI) on the payload bay (PLB) door exterior exposed surfaces, and the reinforced carbon-carbon (RCC) panels on the Orbiter wing leading edge. Damage is documented if it exceeds the threshold size for each Orbiter surface as noted in Table 1. These thresholds have changed between 1992 and 2002 due to modification of Hypervelocity Impact Test Facilities finite element model and represent the current inspection standard. In total, these areas represent only about 10% of the orbiter vehicles total exposed surfaces. The rest of the Orbiter is covered with thermal protection system (TPS) materials such ceramic tiles and blankets. [Ref. 1]

Region Inspected	Damage Size Threshold (mm)	Area (m^2)
Windows	0.25	3.6
Radiator Panels	1.0	117
RCC	1.0	41
FRSI	1.0	40

Table 1 Threshold for reporting damage and inspected surface area of Shuttle Orbiter Vehicle regions

Impact damage is common to the TPS tiles (from 50 to 200 tile damage sites are normal after each mission), but most of the damage is due to low-speed impacts to the vehicle during launch and ascent (i.e., from insulation, ice, and other material coming off the solid rocket boosters or external tank). [Ref. 3] Also, if a tile is damaged either during ascent or on-orbit, the damage site is typically modified later in the mission during descent by aerodynamic heating and erosion of the relatively fragile insulation, which makes it more difficult to assess the cause of the damage. [Ref. 2]

Inspection criteria and techniques have changed with operational changes at KSC. Since STS-82, only impact damage to the radiator panels that goes through the thermal tape overlay and damages the radiator facesheet or honeycomb structure is cataloged. Prior mission inspections recorded all radiator impacts that were greater than 0.8 mm. For missions after STS-82, an optical micrometer and fiber optic light source is used to identify window damage. The increased sensitivity of this equipment results in an increased number of reported and cataloged window impacts. [Ref. 2]

C. ORBITER COMPONENT LOCATIONS AND SCHEMATICS

Figure 1 shows Space Shuttle Orbiter Vehicle locations that are subject to post-flight M/OD surveys: Windows, Radiators and RCC. Other areas inspected include beta cloth, Ku-band antenna, rudder speed break, vertical stabilizer, and TPS tiles, but are not part of the normal survey. [Ref. 4]

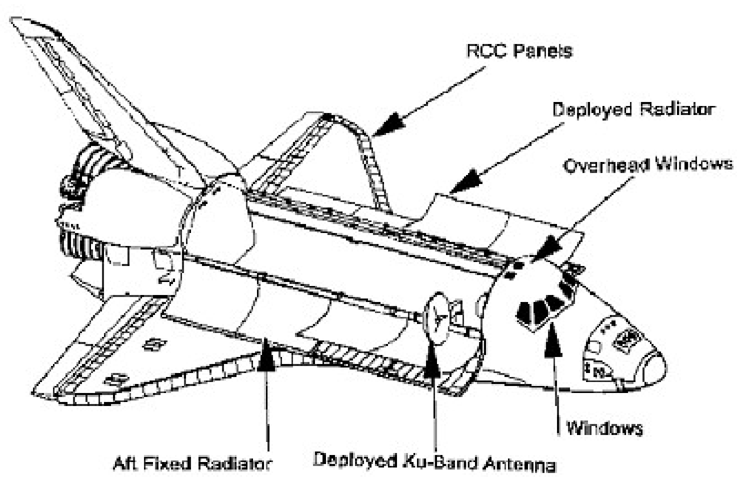

Figure 1 Orbiter Windows, Radiators, and RCC (from Ref 2)

1. Windows

Figure 2 shows 9 of the Orbiter's windows. Each of the windows consists of three glass panes: an outer thermal pane (Corning 7940 fused silica glass) and two pressure panels. The 8 central windows are specified as left and right hand: forward, middle, side and overhead. The windows are numbered 1-8, starting with the left side window and proceeding clockwise, so that the left overhead window is number 8. Also shown is a window in the side hatch, window number 11. There are two other windows in the Orbiter overlooking the payload bay (number 10 left and number 9 right) and another window in the airlock hatch (they are not shown here) [Ref. 2]

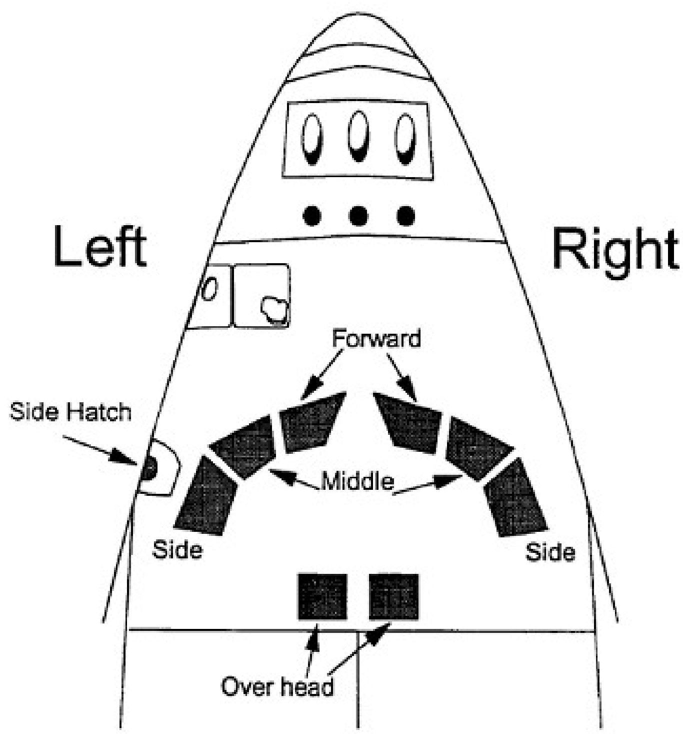

Figure 2 Orbiter Windows (from Ref 2)

2. Radiators

Figure 3 and Figure 4 show the layout for the Orbiter's radiators. The radiators consist of 8 panels divided into starboard and port, forward (No. 1 and 2) and aft (No. 3 and 4) panels. Each radiator panel is a 4.6m x 3.2m curved aluminum honeycomb

structure from 13mm (aft) to 23mm (forward) thick with 0.28mm thick aluminum (2024-T81) facesheets. A silver-Teflon thermal control tape is bonded to the exterior. Freon is pumped through aluminum coolant tubes that are mounted at periodic intervals under the facesheets within the honeycomb. The forward radiator panels can be deployed (35.5° at the hinge line) although thermal requirements seldom cause them to be deployed in practice. [Ref. 1]

Figure 5 shows a radiator M/OD upgrade, which began in 1997. The upgrade includes aluminum doubler plates (0.02" H x 0.04"W) attached to the facesheet directly over the radiator coolant tubes. Also added, but not shown here, were cooling loop isolation valves. These valves allow for isolation of damage if a penetration occurs in the coolant line. Typically, the loss of a radiator coolant loop would be cause for a mission abort. These modifications significantly mitigate the risk of a coolant tube penetration. [Ref. 5]

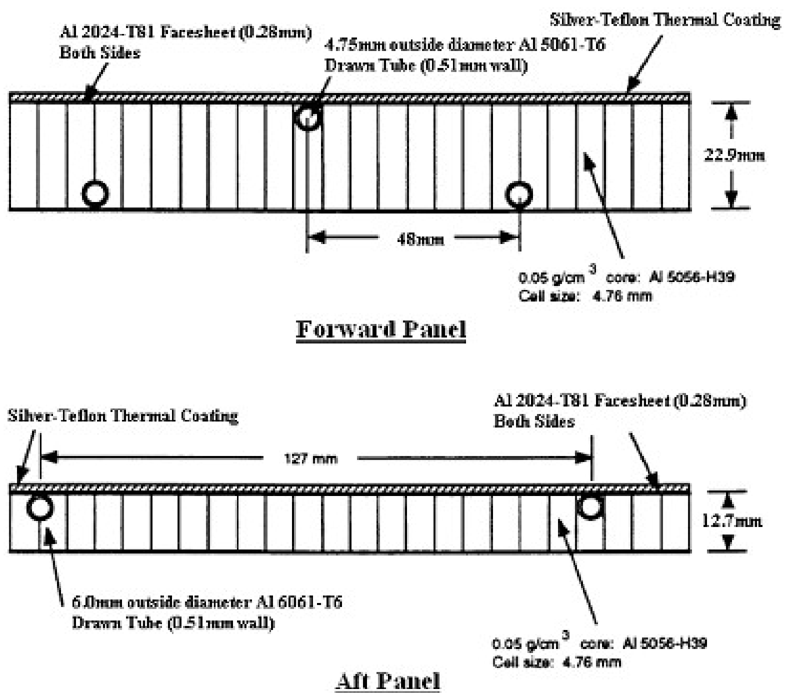

Figure 3 Cross-sectional diagram of forward and aft Orbiter radiator panels showing the Silver-Teflon coating, aluminum facesheet and honeycomb core (from Ref 2)

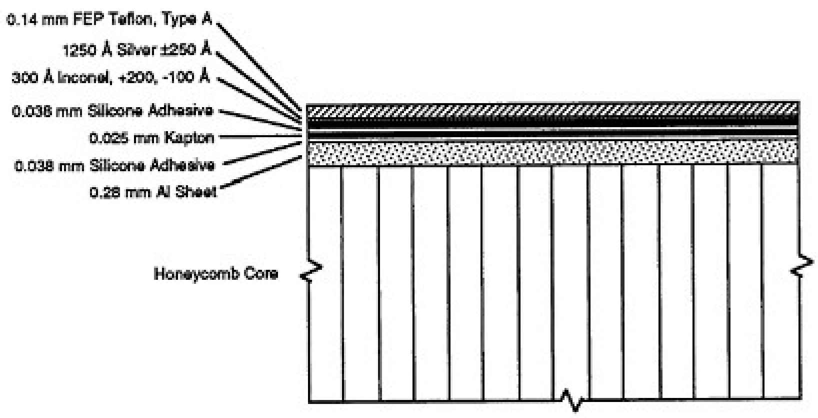

Figure 4 Radiator Silver-Teflon thermal tape (from Ref 2)

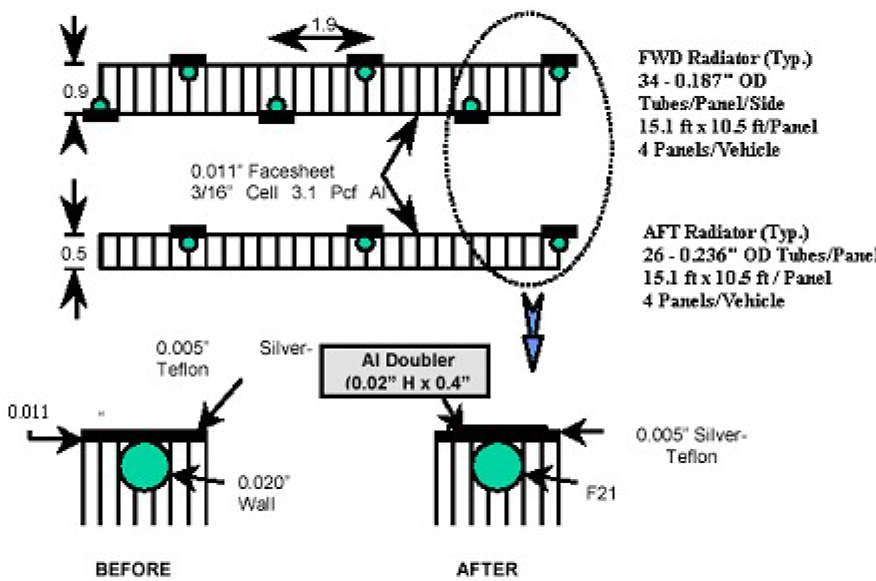

Figure 5 Payload Bay Door Radiator M/OD Upgrade (from Ref 5)

3. Reinforced Carbon-Carbon (RCC)

Figure 6 and Figure 7 show the schematics of the wing leading edge RCC. The RCC is a structural composite used as the thermal protection system for the high-temperature areas of the orbiter. These areas include the wing leading edge, nose cap, an area between the nose landing gear door and nose cap, and a small area surrounding the forward attach fitting of the external tank to the orbiter. Most RCC is in the wing leading edge panels (40.6 m^2). [Ref. 5]

RCC typical overall thickness is 6.3mm, consisting of 4.3mm to 5.3mm thick all-carbon substrate (density of 1.44 g/cm3 to 1.6g/cm3) that has been coated on either side with a dense 0.5mm to 1.0mm thick silicon-carbide layer formed in a diffusion reaction process. [Ref. 5]

A wing leading edge M/OD upgrade was made in 1997, which addressed the potential vulnerability of the wing leading edge attachment structure to re-entry heating due to a M/OD perforation of an RCC panel. The upgrade involved the installation of Nextel fabric to the Cerachrome insulation at the four locations where each RCC panel mounts the wing leading edge spar structure. The modification permits the Shuttle program to accept a larger diameter hole in the RCC panels, resulting in a reduced critical penetration risk. Figure 8 details the upgrade.

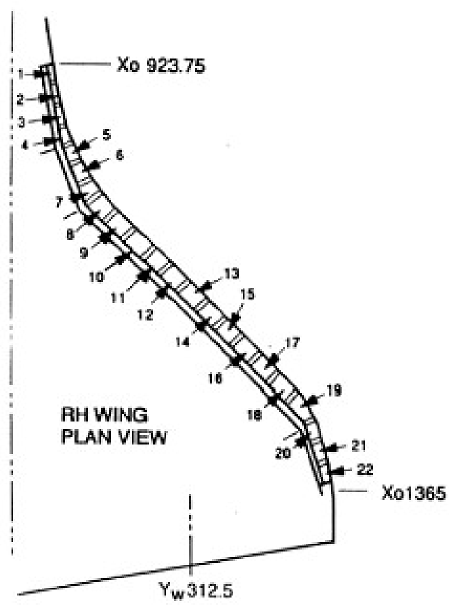

Figure 6 Orbiter wing RCC (from Ref 5)

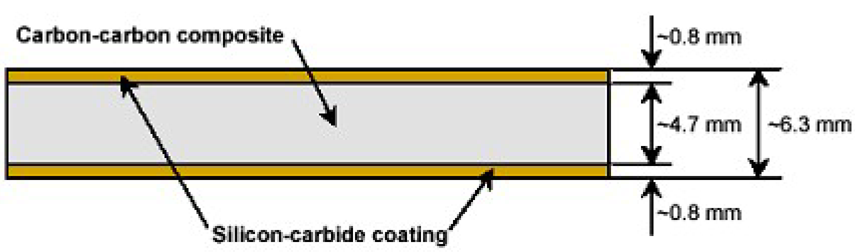

Figure 7 RCC Cross-section (from Ref 5)

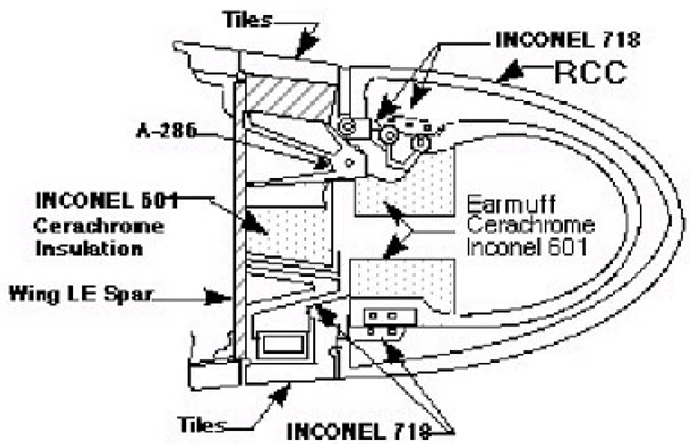

Figure 8 Wing Leading Edge RCC M/OD Upgrade (from Ref 5)

4. Flexible Reusable Surface Insulation (FRSI)

Figure 9 shows a cross-section of the payload bay door FRSI lay-up. Approximately 70% of the exterior of the payload bay doors are covered with FRSI which consists of a Nomex felt pad and white rubberized coating. The silicon coating in the figure below is the outermost layer. [Ref. 5]

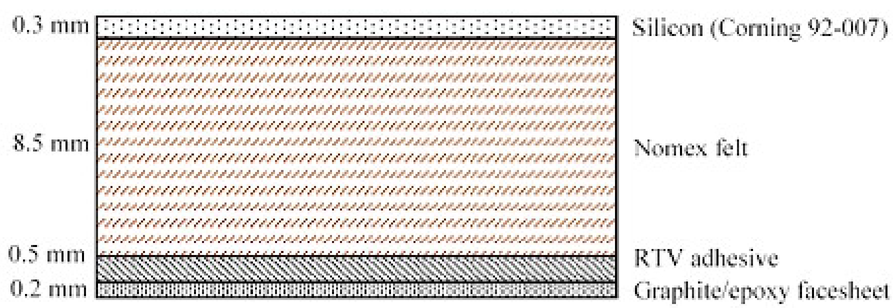

Figure 9 Payload Bay Door FRSI cross-section (from Ref 5)

D. IMPACT SITE ANALYSIS

After the post-flight inspection is completed, JSC personnel analyze samples extracted from the impact sites using a scanning electron microscope (SEM) equipped with energy dispersive X-ray spectrometers (EDXA). Such techniques allow engineers to determine whether the impactor was a naturally occurring meteoroid or man-made orbital debris. In addition, comparisons to hypervelocity impact (HVI) experiments allow engineers to determine the appropriate size and impact velocity. The Orbital Debris

program uses these data to validate the existing M/OD environment and to improve its fidelity. [Ref. 1] A more detailed description of the sampling methods and analysis is discussed in the next chapter.

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II. SHUTTLE IMPACT DATABASE

A. DATABASE

The Shuttle Hypervelocity Impact Database is a Microsoft Excel spreadsheet, which is a record of 2,067 cataloged impacts from naturally occurring meteoroids and man-made orbital debris on the shuttle orbiters, as seen from 50 post-flight inspections between STS-50 in 1992 and STS-110 in 2002. No data was collected from missions STS-53, 54, 55, 57, 58, 62, 67, 69, 74, and 78. Only about 10 percent of the orbiters surface area is inspected. Current practice calls for documentation of all Hypervelocity Impact (HVI) damage that exceeds thresholds in Table 1 that occur to Windows, Radiator Panels, Reinforced Carbon-Carbon and Flexible Reusable Surface Insulation on the outer payload bay doors. [Ref. 2]

The data is cataloged in six different worksheets: Mission Information, Window Impact Data, Window Replacement Data, Radiator Impact Data, Radiator Facesheet Perforation Data and Other Impact Data. Also included in the database are two summary pages, Windows Stats and Radiators Stats, and exposure times for each orbiter. Below are descriptions of the six main worksheets.

1. Mission Information

The mission information worksheet is a listing of parameters for each mission. These parameters are inclination, altitude, duration, year, primary payload, regions surveyed for M/OD impacts, area (mm^2) surveyed, and average mission velocity (km/s).

2. Window Impact Data

Window Impact Data is a listing of every M/OD impact to a window on the Orbiter Vehicle. Associated with each window impact are mission, window number, replacement (Y or N), crater dimensions (length x width x depth), estimated impactor dimensions (diameter and length), SEM/EDXA results along with SEM particle type and assessed particle type, particle density, impact velocity, impact angle and average crater diameter.

3. Window Replacement Data

Window Replacement Data breaks each mission into mission length, windows replaced per mission (each window as well as cumulative windows) and window replacement rate per mission.

4. Radiator Impact Data

Radiator Impact Data is a listing of every M/OD impact to the Payload Bay Door Radiators on the Orbiter Vehicle. Associated with each radiator impact are mission, panel number, tape hole diameter (length and width), facesheet damage (length x width x depth), estimated impactor diameter, SEM/EDXA results along with SEM particle type and assessed particle type, particle density, impact velocity, and average tape hole diameter.

5. Radiator Facesheet Perforation Data

Radiator Facesheet Perforation Data breaks each mission into mission length, total radiator impacts, total facesheet perforations, and perforation rate.

6. Other Impact Data

Other Impact Data includes data for all RCC and FRSI impacts on the Orbiter Vehicles, as well as impact data for all other cataloged impacts, such as beta cloth, Ku-band antenna, rudder speed break, vertical stabilizer, and TPS tiles. Areas outside RCC and FRSI are not normally inspected or cataloged, but are done so upon special request or if am impact is large enough to bring attention to itself. Associated with these impacts are mission, location, damage dimensions for craters (length x width x crater depth) and holes (length x width), SEM/EDXA results along with assessed particle type, and average crater or hole diameter.

Although the spreadsheet is titled as a database, it is really just a spreadsheet. It is great for number crunching and provides flexibility for the manipulation of columns and rows, but it is very labor intensive and difficult to relate data, other than what is pre-programmed. For example, information contained in the Mission Information, Window Data, Radiator Data, and Other Impact Data worksheets cannot be related to on another without manipulating the data in a time and labor intensive manner. Also, the spreadsheet does not allow a query of the data and does not generate reports, outside what

is pre-programmed. A relational database may prove to be a better medium for storage and access of the data. In a relational database, queries can be made to relate data from any of these worksheets, and then turned into a report designed by the user. Also, when updating the database the manager can make changes all at once, instead of making changes to every separate worksheet within the spreadsheet. This reduces time and duplication.

B. SAMPLING TECHNIQUES

M/OD impacts are identified in the post-flight inspections by one or more of the following sampling methods: a sample plug or core including the impact site was extracted; an epoxy mold impression was made of the impact site; a dental mold impression was made of the impact site; a piece of adhesive tape was applied to the impact site and pulled up to gather projectile debris; or a probe made of soft wood (e.g. a toothpick) was used to gather projectile debris. [Ref. 2] Samples are analyzed by scanning electron microscopy equipped with energy dispersive x-ray spectrometers (SEM/EDX) to image the shape of the impact and to determine the elemental constituents of any remnant projectile particles. This analysis leads to a determination of the origin of the impacting projectile; i.e., whether natural meteoroid or man-made orbital debris, using established classification methods. [Ref. 6 and 2]

In some cases, the SEM/EDX analyses are listed as “unknown.” In these cases, no identifiable projectile materials were found in or around the impact point. [Ref. 2] There are a number of possible explanations for this result:

(1) The sample technique did not capture any projectile materials. The sampling method of choice with the greatest likelihood of obtaining a sample with impact residues is of course a sample with the actual impact, either by extracting a “core” or cutting a piece of the impacted material. However, often epoxy or dental molds, or tape pull samples must be used because the Orbiter must be returned to service in a timely manner, and obtaining M&OD samples is sometimes in conflict with this requirement. Other means are used to extract a projectile sample if the actual damaged site cannot be collected. Epoxy molds provide excellent means of sampling window impacts. Dental

molds and tape pull samples work well on radiators, however they usually are less successful for sampling window glass impacts. [Ref. 2]

(2) The target surface and impacting particle consist of approximately the same materials. An example of this is an aluminum impactor striking the aluminum radiator facesheet. The aluminum in the projectile cannot easily be distinguished from the aluminum in the target. [Ref. 2]

(3) The impact velocity is so high or the impacting materials are so volatile that the impacting particle completely vaporizes. This usually occurs for meteoroids (high velocity & volatile materials), ices/frozen liquids, or plastic materials (some orbital debris). [Ref. 2]

(4) The target is so brittle, such as for windowpanes, that the projectile is ejected with a large quantity of material lost from the target. Some of the impacting particles are identified as spacecraft paint. The primary inorganic components of spacecraft paint are pigments and binders. Organic components are usually lost or vaporized from the heat released in the impact process, except if the impact occurs at low speeds (< 3 km/s) and/or on soft, low density target materials where impact shock heating is reduced. The pigments consist of varying amounts of titanium oxide, zinc oxide, or lead while iron oxide is used for primer type paints. Binders include chlorine, sulfur, sodium, potassium, aluminum, silicon, and magnesium. Concluding that a particular impactor was spacecraft paint is based on the detection of paint pigments (titanium and/or zinc oxides) in the residues left at the impact site. [Ref. 6] Some or all of the inorganic paint binder components are often detected as well. Sometimes organic binders (oxygen, hydrogen, or carbon) are also detected. [Ref. 2]

III. DATA ANALYSIS

A. ARC

The statistical tool used for analysis of the NASA Shuttle Hypervelocity Impact Database is a program called Arc. Arc is a user-friendly computer software package, written in the Xlisp-Stat environment, designed specifically for regression analysis, the study of how a response variable depends on one or more predictors. It uses graphical methods, most based on simple boxplots and two-dimensional scatter plots that provide analysts with more insight into their data than would have been possible otherwise, including a deeper appreciation for interpretation. To use Arc, knowledge of programming in Xlisp-Stat or any other language is not required. [Ref. 7]

Xlisp-Stat represents an attempt to develop a complete statistical environment based on the Lisp language. It consists of a Lisp system with modifications to standard Lisp functions to support vectorized arithmetic operations, a comprehensive set of basic statistical operations, an interface to a window system, support for dynamic graphics within a window system, and an object-oriented programming system that is used to support graphics programming and to represent statistical models, such as linear and non-linear regression models. It can be used as an effective platform for a large number of statistical computing tasks, ranging from basic calculations to customizing dynamic graphs. [Ref. 8]

B. REGRESSION ANALYSIS

The primary goal in a regression analysis is to understand, as far as possible with the available data, how the conditional distribution of the response y varies across subpopulations determined by the possible values of the predictor or predictors. This is expressed as $y \mid x$. The vertical bar in this notation stands for the word *given*. For example, we may refer to the distribution of *Total Window Hits* | *Year*, which means the distribution of *Total Window Hits* in the subpopulation determined by the value of mission *Year*. [Ref. 7]

The mean and variance of $y \mid x$ are represented by $E(y \mid x)$ and $Var(y \mid x)$. As we move from subpopulation to subpopulation by changing the value of x, both $E(y \mid x)$ and $Var(y \mid x)$ may change. This points out that both $E(y \mid x)$ and $Var(y \mid x)$ are functions of the variable x, and therefore are known as the mean function and variance function. The standard deviation function is just the square root of the variance function. [Ref. 7]

C. GRAPHICAL CORRELATION

The regression analysis conducted on the Shuttle Hypervelocity Impact Database relies heavily on graphical methods, mostly using the boxplot and scatterplot. Below are explanations of each.

1. Boxplot

The boxplot is a pictorial summary used to describe several of a data set's most prominent features. These features include center, spread, the extent and nature of any departure from symmetry, and identification of 'outliers', observations that lie usually far from the main body of the data. Comparative boxplots, or side-by-side boxplots are a very effective way of revealing similarities and differences between two or more data sets consisting of observations on the same variable. [Ref. 9]

A boxplot, as seen in Figure 10 consists of a box with a horizontal line through it, and two vertical lines extending from the upper and lower boundaries of the box. The line through the box marks the location of the median relative to the vertical axis of the plot. The lower edge of the box marks the location of the first quartile, q(.25) and the upper edge marks the third quartile, q(.75). The box contains 50 percent of the observations. The width of the box contains no relative information. [Ref. 7]

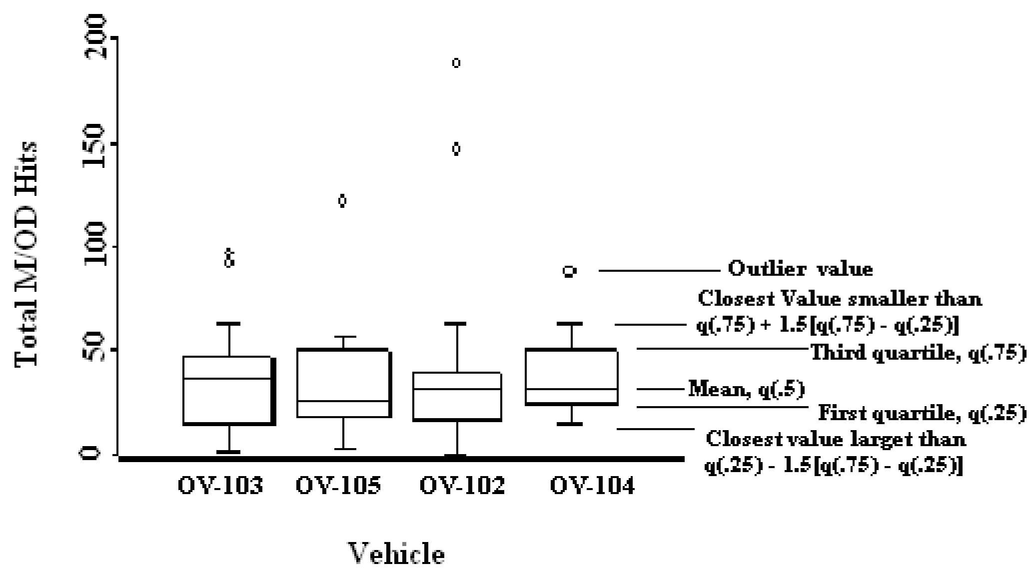
The line extending down from the box terminates at the data point that is closest to, but larger than

$$L = q(.25) - 1.5[q(.75) - q(.25)]. \text{ [Ref. 7]}$$

Data points with values smaller than L are called lower outlier values. Similarly, the line extending up from the box terminates at the data point being the closest to, but smaller than

$$U = q(.75) + 1.5[q(.75) - q(.25)]. \text{ [Ref. 7]}$$

Data points with values larger than U are called Upper outlier values. [Ref. 7]




```
Analysis of Variance
Groups:   DF =    3, MS = 396.231
Residual: DF =   46, MS = 1419.99
F =   0.28, p-value = .8402
```

Figure 10 Boxplot of Total Meteoroid/Orbital Debris Hits conditioned on Orbiter Vehicle

Also shown in Figure 10 is an Analysis of Variance (ANOVA). The ANOVA tests if all the means are plausibly the same, and return a p-value indicating how likely these results are if the means are all the same. The idea behind ANOVA is that the sample averages should be close to each other, if the model is true. [Ref. 10]

The p-value, as defined by Devore, is the

smallest level of significance at which the null hypothesis (H_o) would be rejected when a specified test procedure is used on a given data set. Once

> the p-value has been determined, the conclusion at any particular significance level (α) results from comparing the p-value to α. [Ref. 9]

If the p-value is less than or equal to α, then reject H_o at the level α. If the p-value is greater than α, then do not reject H_o at the level α. It is customary to call the data significant when H_o is rejected and not significant otherwise. An alternative definition of p-value, provided by Devore, is

> the probability, calculated assuming the null hypothesis (H_o) is true, of obtaining a test statistic at least as contradictory to H_o as the value that actually resulted. The smaller the p-value, the more contradictory is the data to H_o. [Ref. 9]

So, for the boxplot in Figure 10, the null hypothesis is that the average number of total meteoroid and orbital debris hits is the same for each orbiter vehicle. The significance level α is set at 0.05 (a customary value). Since the p-value returned in the ANOVA is 0.8402 (p-value > α), the null hypothesis that the averages are the same is not rejected. Another way of stating this is that since the p-value is larger than 0.05, it is concluded that the average number of meteoroid and orbital debris hits to the orbiter vehicle is plausibly the same across the orbiter vehicle fleet.

In conclusion, the boxplot is a very useful way of describing the features of a data set or groups of data sets, and ANOVA is a very powerful technique for establishing differences in means between multiple groups.

2. Scatterplot

The scatterplot is a useful graphical display that shows how the conditional distribution of $y \mid x$ changes with the value of x. Two-dimensional scatterplots for a regression with a single predictor are usually constructed with the predictor along the horizontal axis and the response along the vertical axis. Figure 11 below is an example of this. [Ref. 7]

Figure 11 Scatterplot of Total Meteoroid/Orbital Debris Hits vs. Year

Figure 12, seen below, is the same scatterplot as Figure 11, but has two lines fitted to the data points; an Ordinary Least Squares (OLS) estimate line, also called an estimated regression line, and a Lowess smooth line.

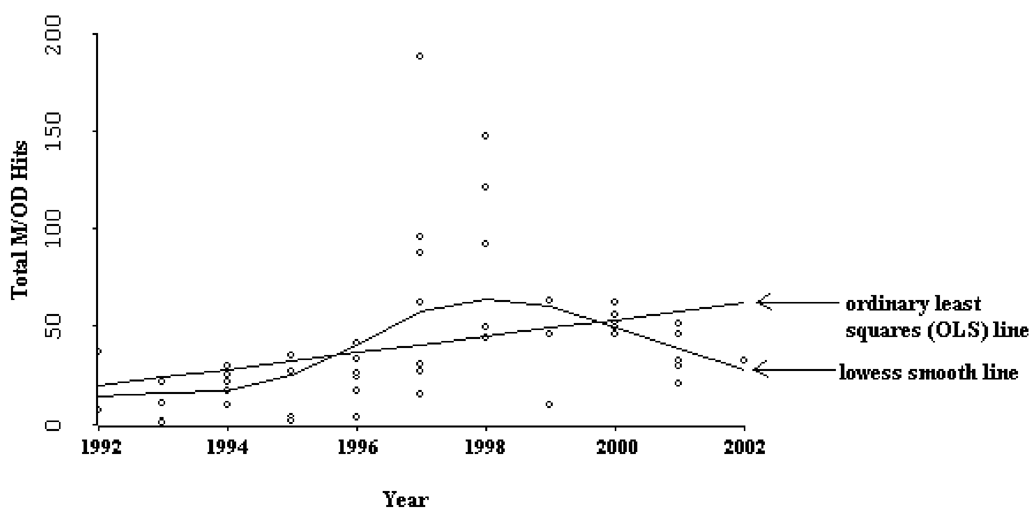


Figure 12 Scatterplot of Total Meteoroid/Orbital Debris Hits vs. Year with Ordinary Least Squares line and Lowess smoother line

The principal of least squares, best described by Devore, is stated below.

The vertical deviation of the point (x_i, y_i) from the line $y = b_0 + b_1x$ is

height of point - height of line = $y_i - (b_0 + b_1x_i)$

The sum of squared vertical deviations from the points (x_1, y_1), …, (x_n, y_n) to the line is then

$$f(b_0, b_1) = \sum_{i=1}^{n} [y_i - (b_0 + b_1x_i)]^2$$

The point estimates of β_0 and β_1 denoted by $\hat{\beta}_0$ and $\hat{\beta}_1$ and called the least squares estimates, are those values that minimize $f(b_0, b_1)$. That is, $\hat{\beta}_0$ and $\hat{\beta}_1$ are such that $f(\hat{\beta}_0, \hat{\beta}_1) \leq f(b_0, b_1)$ and for any b_0 and b_1. The estimated regression line or least squared line is then the line whose equation is $y = \hat{\beta}_0 + \hat{\beta}_1 x$. [Ref. 9]

Cook best describes the Lowess smoother, below.

The Lowess smoother is a locally weighted scatterplot smoother. For a two-dimensional scatterplot of y versus x, a fitted value of $\hat{y}_l$ at a particular point x_l is obtained as follows. (1) Select a value for a smoothing parameter f, a number between zero and one, for example, set f = 0.6. (2) Find the fn closest points to x_l, for example, if n=100, find the fn=60 closest points. (3) Among the *fn nearest neighbors* to x_l, compute the [weighted least squares] estimates for the regression of y on x, with weights determined so that points close to x_l have the highest weight, and the weights decline toward zero for points farther from x_l. We use a triangular weight function that linearly decreases from a maximum value at x_l to zero at the edge of the neighborhood. (4) Return the fitted value at x_l. (5) Repeat 1-4 for many values of x_l and join the points. [Ref. 7]

The calculations to create the OLS and the Lowess smooth line are performed automatically by Arc, and are transparent to the user. It is important, though, to understand the mathematics behind these calculations to fully appreciate the value of the graphical data presented by Arc.

The reason for having these two calculations overlaid onto a scatterplot is to evaluate trends in the data. In Figure 12, the OLS shows an increasing trend in the

number of meteoroid and orbital debris hits from 1992 to 2002. This is interesting enough, but the Lowess smoother line shows that the data does not exactly fit best to a straight line, but has some curvature to it. Both the slope of the OLS and the curvature must be evaluated for statistical significance before any conclusions can be drawn.

The slope of the OLS and the curvature of the Lowess smoother can be evaluated with the p-value. The p-value for the OLS is obtained in Arc from the regression summary for that line. The null hypothesis is that the slope of the OLS line is zero. For the example in Figure 12, the p-value associated with the regression line, or OLS, is 0.0232. Since this value is less than 0.05, the slope is statistically significant, and it can be said that there is a statistical increase in the number of meteoroid hits between 1992 and 2002. A test for curvature of the Lowess line can also be easily computed in Arc. In this example, the p-value associated with the test for curvature is 0.008. Since this value is also less than 0.05, it can be said that there is in fact statistically significant curvature to the Lowess line, and therefore the data does not best fit a straight line. The reasons for curvature of this line can then be evaluated later.

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IV. ANALYSIS RESULTS

A. TOTAL M/OD IMPACT DATA

An analysis of NASA's Shuttle Hypervelocity Impact Database was conducted to find correlations between Meteoroid and Orbital Debris impacts on the Shuttle Orbiter fleet and specific mission parameters seen in Appendix A; Inclination, Altitude, Duration and Year. Although these mission parameters are cataloged in the mission information section of the database, it is not apparent how they affect (as predictors) Meteoroid and Orbital Debris (M/OD) damage.

The database, a MS Excel spreadsheet, catalogs 2067 M/OD impacts on the shuttle orbiter fleet. It is broken into several categories (mission information, window data, radiator data, other data), but none of these categories are related to each other. These categories were combined into one worksheet to account for every impact, regardless of impact location, to relate mission information to total impacts on the shuttle vehicles. An analysis was then conducted to determine possible correlations between mission parameters (inclination, altitude, duration, year) and M/OD damage to the shuttle orbiter fleet.

1. Mission Inclination

Since 1992, the space shuttle orbiters have flown at four inclinations: 28.5-deg, 39-deg, 51.6-deg, and 57-degrees. The choices for these mission inclinations were driven by either mission requirement or by cost constraint.

An assumption prior to analysis was that inclination would not be a good predictor for M/OD damage to the shuttle orbiter fleet. Man-made debris orbiting the earth can come from many sources, but is most likely a result of fragmentation from rocket staging, internal explosion, collision, unplanned or deliberate, or from paint flaking due to solar radiation and atomic oxygen effects. As this fragmentation debris is released, it is inserted into orbits of different inclinations and at different velocities. A result of these varied inclinations and velocities is a toroidal cloud. Figure 13 shows the

evolution of this debris cloud. Phase 1 of the cloud evolution shows the initial spacecraft in proper orbit. As fragmentation commences, the debris begins to spread, as seen in Phase 2, until the cloud eventually reaches a point, similar to Phase 3, where only maximum inclinations and altitudes limit the debris. [Ref. 11]

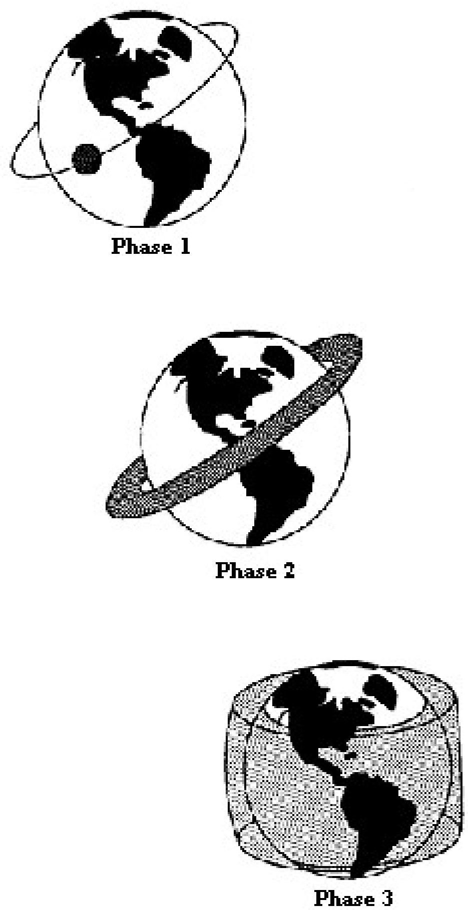

Figure 13 Debris Cloud (from Ref 11)

Since naturally occurring meteoroids enter the earth's atmosphere and are inserted into orbits from random directions, the debris cloud discussed above will also be populated with micrometeoroids. With a debris cloud made up from the fragmentation of many satellites and rocket bodies, as well as micrometeoroids, it is easily assumed that any orbital inclination flown will be within this debris cloud. Thus, collision with meteoroids or man-made orbital debris is likely at any inclination.

Figure 14 is a representation of the low earth orbit objects currently tracked by USSPACECOM. These objects are greater than 200mm in diameter and include

functional and dysfunctional spacecraft, as well as orbital debris. It is assumed that the debris cloud with object sizes comparable to those impacting the orbiter fleet is similar to the figure below. [Ref 12]

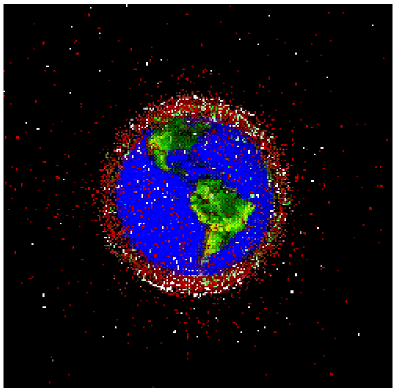

Figure 14 LEO objects tracked by USSPACECOM (from Ref 12)

Figure 15 below shows a scatterplot of Total Meteoroid/Orbital Debris Hits per (Shuttle) Mission vs. inclination. Each mark in the plot is a different mission, and each of the four different symbols represents the orbiter flown in that mission. The average number of M/OD hits on the shuttle orbiter vehicles, independent of location, is 41.2 hits per mission with a standard deviation of 36.8. Figure 16 is a boxplot of the same information, but shows the mean value of Total M/OD Hits per Mission for each of the four inclinations shown. Although the means are different, they are within one standard deviation of the average, and are therefore statistically the same across all four inclinations.

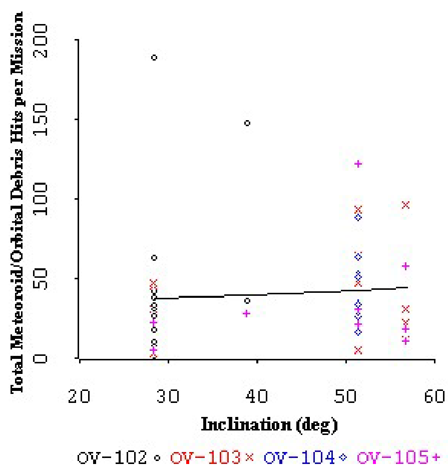

Figure 15 Total Meteoroid/Orbital Debris Hits per Mission vs. Inclination

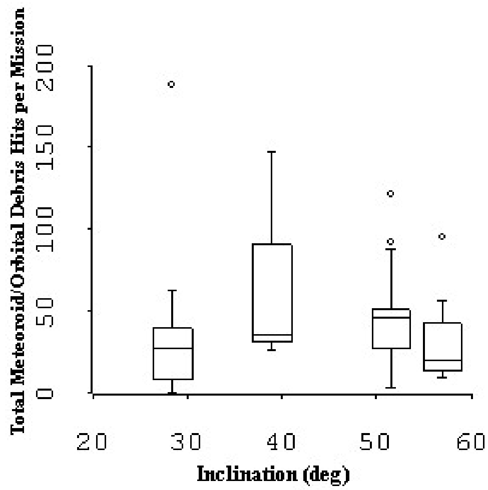

Figure 16 Boxplot of Total Meteoroid/Orbital Debris Hits per mission conditioned on Inclination

To normalize the data, a flux, or Hit Rate, defined as Total M/OD Hits per Mission per Day, was calculated and plotted against inclination. As seen in Figure 17, the average M/OD hit rate, regardless of hit location, is 3.7 hits per mission per day, and is statistically the same across the four inclinations flown.

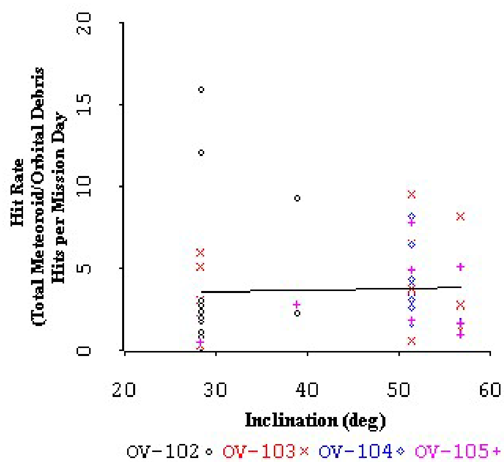

Figure 17 Total Meteoroid/Orbital Debris Hit Rate vs. Inclination

A look at Meteoroid Hit Rate vs. Inclination and Orbital Debris Hit Rate vs. Inclination show averages of 0.66 and 0.71 hits per mission per day respectively across all four inclinations flown, and are within one standard deviation of each other. The hit

rate for unknown objects (objects that were unable to be classified as naturally occurring meteoroid or man-made orbital debris) is 2.3 hits per mission per day.

These numbers suggest that the assumption of inclination not being a good predictor for M/OD damage is valid. Any mission flown at a particular inclination is likely to receive just as many hits from meteoroids or orbital debris as in any other inclination.

2. Mission Altitude

The shuttle fleet has flown at many different altitudes, ranging from 222 km to 594 km, between 1992 and 2002. It was assumed, prior to analysis, that altitude would be a good predictor for M/OD damage to the shuttle orbiter fleet, and that there would be a greater hit rate in the lower altitudes than in the higher altitudes, as all debris passes through this region prior to reentry.

A scatterplot of Total M/OD Hits per Mission vs. Altitude, seen in Figure 18, shows that the average number of M/OD hits per mission is statistically the same across all altitudes flown. There seem to be more M/OD hits in the lower altitudes, but that can be attributed to more missions flown in lower altitudes than higher.

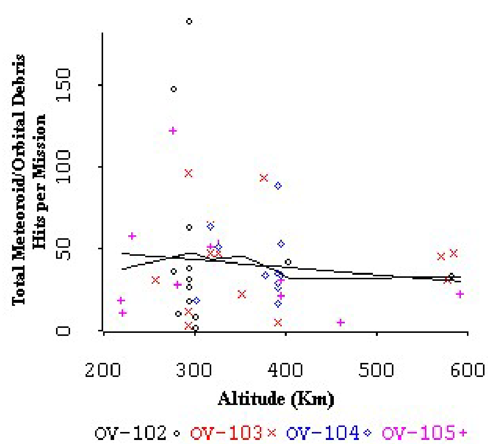

Figure 18 Total Meteoroid/Orbital Debris Hits per Mission vs. Altitude

To normalize the data, a flux, or Hit Rate, defined as Total Meteoroid/Orbital Debris Hits per Mission per Day, was plotted against Altitude. As seen in Figure 19, the average M/OD hit rate, regardless of hit location, is 3.7 hits per mission per day, and is

statistically the same across all altitudes flown. A look at Meteoroid Hit Rate vs. Altitude and Orbital Debris Hit Rate vs. Altitude also reveal consistent hit rates across all altitudes flown.

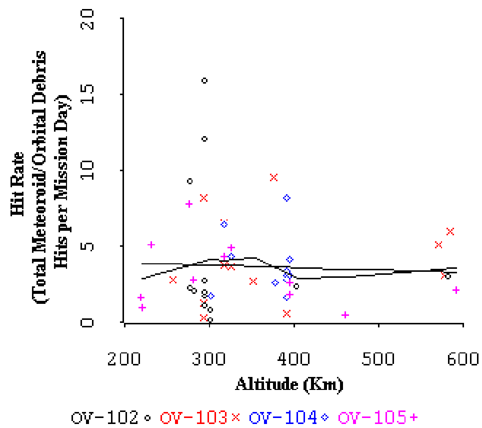

Figure 19 Total Meteoroid/Orbital Debris Hit Rate vs. Altitude

These numbers suggest the assumption that altitude would be a good predictor for M/OD damage was invalid. Any mission flown at a particular altitude is likely to receive just as many hits from meteoroids or orbital debris in any other altitude, within the flight range of the shuttle missions between 1992 and 2002.

3. Mission Duration

It was expected that longer duration flights would experience more M/OD impacts than shorter duration flights, simply due to longer exposure time. This assumption is shown to be correct, as seen in Figure 20.

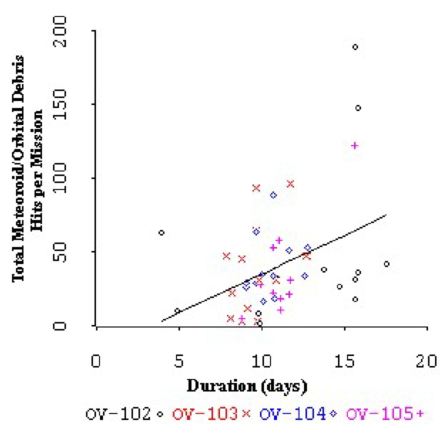

Figure 20 Total Meteoroid/Orbital Debris Hits per Mission vs. Duration

A flux, or Hit Rate, defined as Total Meteoroid/Orbital Debris Hits per Mission per Day, was plotted against mission Duration, finding an average of 3.71 M/OD hits per mission day. This hit rate is statistically the same for all durations.

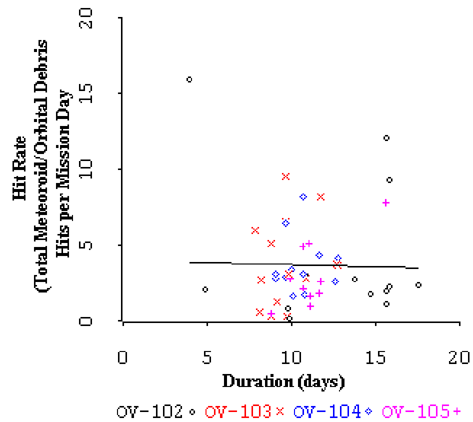

Figure 21 Total Meteoroid/Orbital Debris Hit Rate vs. Duration

4. Mission Year

It seemed natural to see how the database was affected over its lifetime, from 1992 to 2002. There was a 43% increase in total impacts, regardless of impact location, from 1992 to 2002. This is seen in Figure 22, where the Total Meteoroid/Orbital Debris Hits per Mission was plotted over the lifetime of the database. More interesting, though is that the damage seems to follow a cyclic pattern. A closer look at this cyclic pattern shows a 298% increase in total M/OD hits from 1992 to 1998, and a 177% decrease from 1998 to 2002. This is believed to be a result of the solar cycle. A discussion of solar cycle vs. damage cycle is presented below.

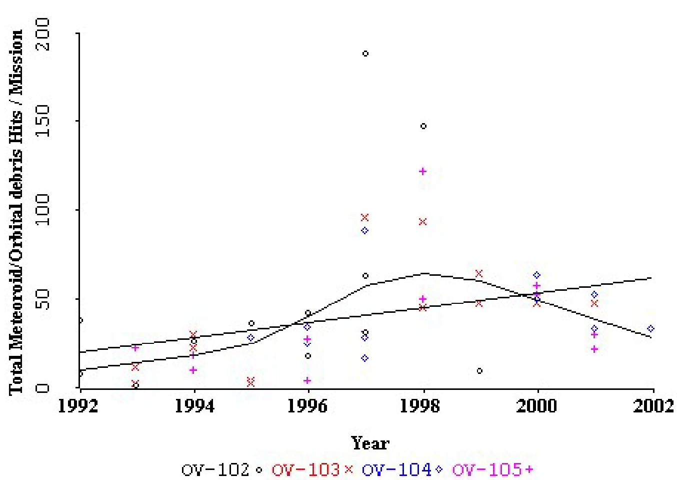

Figure 22 Total Meteoroid/Orbital Debris Hits per Mission between 1992 and 2002

To normalize the data, a flux, or Hit Rate, defined as Total M/OD Hits per Mission per Day, was calculated and plotted against the lifetime of the database, seen in Figure 23. The results were similar to the scatterplot in Figure 22, in that the data seems to follow a cyclic pattern, presumably a result of the solar cycle. There is a 303% increase in hit rate from 1992 to 1998, and a 136% decrease in hit rate from 1998 to 2002.

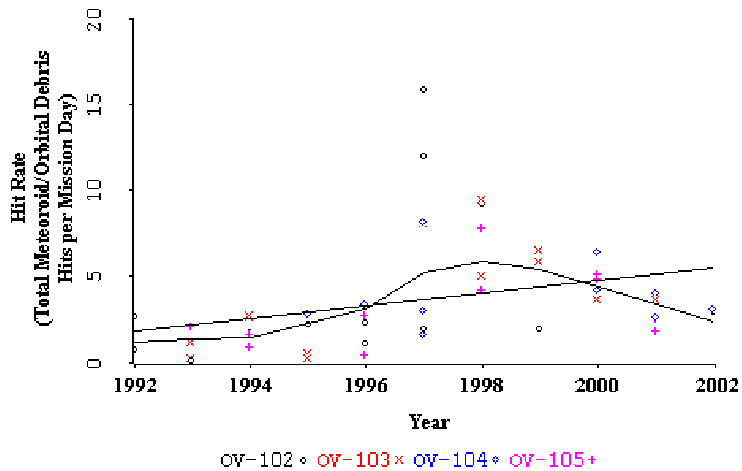

Figure 23 Total Meteoroid/Orbital Debris Hit Rate between 1992 to 2002

B. SOLAR CYCLE

A look at total hits to the orbiter fleet, regardless of location, particle type or mission shows that the Solar Cycle has a direct impact on the damage caused to the shuttle orbiter fleet. A comparison of damage vs. year to the solar cycle indicates that damage occurring to the shuttle orbiters seem to be following a cyclic pattern similar to the solar cycle.

The database currently shows an increasing trend in damage caused to the orbiter fleet. This increasing trend is due to the fact that the database only contains data through part of one solar cycle, from Solar Minimum to Solar Maximum. Because of this, the database is incomplete, and requires a minimum of three more years of data in order to see the effects of one complete solar cycle on the orbiter fleet. For a more proper look at the effects of any cyclic pattern on an event, data should be collected and analyzed over several repetitions of that cycle. As more data is cataloged throughout the rest of the

current solar cycle (to solar minimum), and through several more cycles, the increasing trend seen in this data will level out.

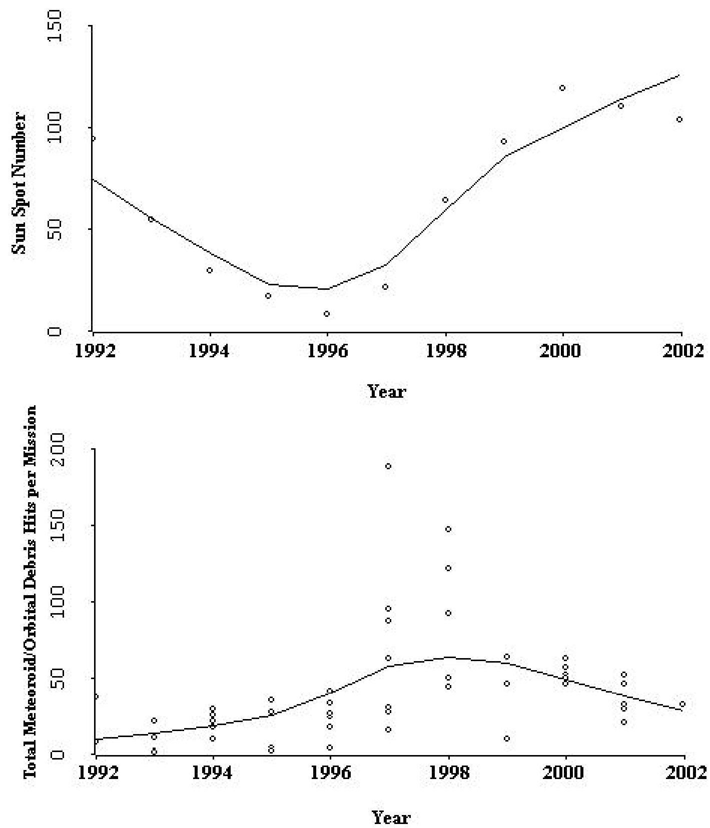

Figure 24 Comparison of Solar Cycle to Meteoroid/Orbital Debris hits to the Shuttle fleet between 1992 and 2002

The top graph's ranges in Figure 24 represent the solar cycle from 1992 – 2002.[Ref. 13] It shows the trailing off from (the known) 1990 Solar Max to the Solar Max peak in 2000. The bottom graph represents the total number of cataloged hits on the shuttle orbiter fleet from Meteoroids and Orbital Debris from 1992 – 2002. A comparison of the two graphs show that the debris environment (that which is hitting the orbiter fleet) follows the cyclic nature of the Solar Cycle, with the debris cycle maxima lagging the solar cycle's minima by a period of about 2 years.

This phenomenon is due to atmospheric heating associated with the 11-year solar cycle. As the atmosphere heats up during periods of Solar Maximum (increased periods

of sun-spot activity and energy emissions), the decay of orbital debris is accelerated. [Ref. 14]

C. WINDOW DATA

Of all of the surfaces surveyed during the post-flight inspections, the orbiter windows provide the most thorough and consistent data. This is due in part because of the relatively small total area required for survey, but also due to the consistent techniques used for analysis and the volume of window impacts cataloged. Of the 2,067 cataloged impacts, 1,578 are window impacts. There are 11 windows on the shuttle orbiter that are inspected for meteoroid and orbital debris damage, which have a combined surface area of 3.6 m^2. Further description of these windows can be found in Chapter 1, and the relative locations of these windows can be seen in Figure 2. Of the 1578 cataloged window impacts in the database, 250 are from meteoroids, 268 from orbital debris, and 1060 from unknown objects.

1. Correlation between Window Hits and Mission Parameters

Correlations between window hits and mission parameters are similar to those for total hits. Inclination and altitude are not good predictors for M/OD damage, as seen in Figure 62 and Figure 63 in Appendix B. Duration and year are good predictors. With longer mission durations, there are more M/OD hits to the windows. The hit rate is 2.83 M/OD window hits per mission day, and is statistically consistent across the orbiter fleet as seen in Figure 25. Meteoroid and orbital debris hit rates are 0.43 and 0.45 hits per mission day respectively. The increase in window hits with longer duration missions is seen in Figure 26 and the hit rate is seen in Figure 27.

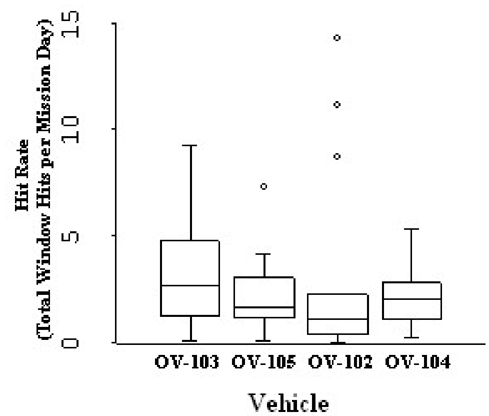

Figure 25 Boxplot of Window Hit Rate conditioned on Vehicle

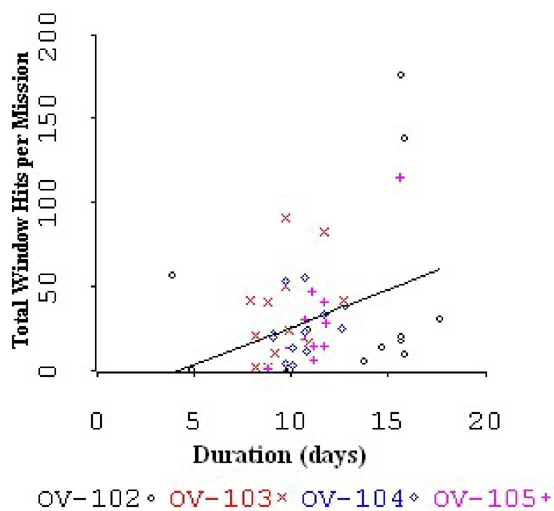

Figure 26 Total Window Hits vs. Duration.

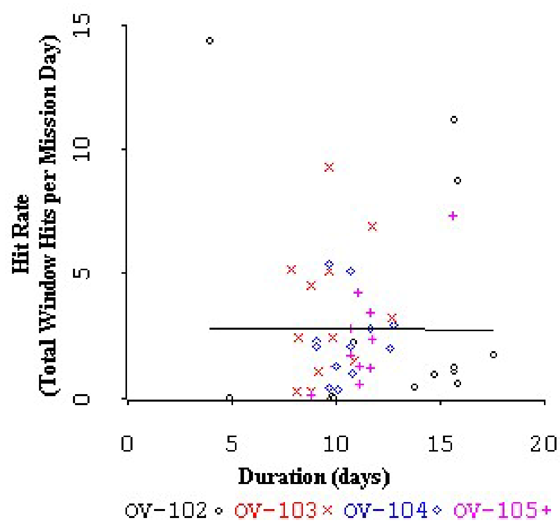

Figure 27 Window Hit Rate vs. Duration

A look at window hits over the lifetime of the database show a cyclic pattern similar to that found for total M/OD hits. There is a 2389% increase in the M/OD window hit rate from 1992 to 1998, and a 207% decrease from 1998 to 2002, as seen below in Figure 28. Meteoroid and orbital debris hit rates on orbiter windows increased 2983% and 1497% respectively from 1992-1998, and decreased 141% and 146% respectively from 1998 to 2002.

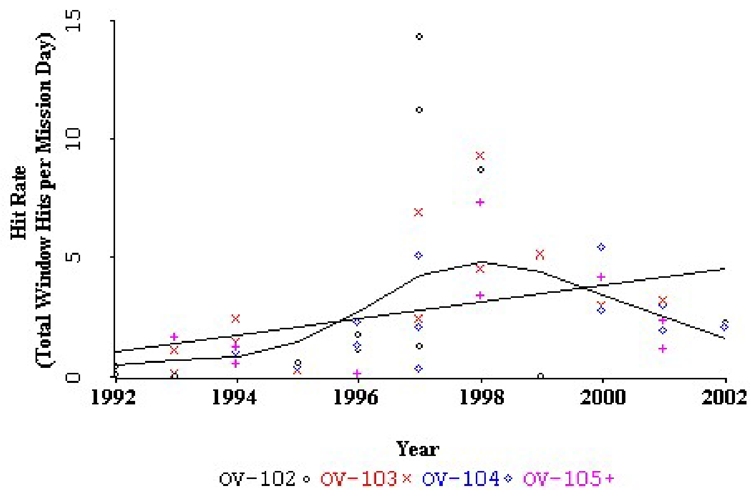

Figure 28 Window Hit Rate between 1992 and 2002

2. Window Damage Size

Analyzing the size of damage to the windows is useful for a variety of reasons. One reason in particular, though not discussed any further in this paper, is for the determination of the impactor size. Another is that safety inspectors use this information for determination of flight safety and window replacement. Analysis shows that average window crater diameters caused by orbital debris are 51% larger than those caused by meteoroids. This is seen in the boxplot below in Figure 29. The average orbital debris crater in orbiter windows is 0.622 mm in diameter, where average meteoroid craters are 0.411 mm in diameter.

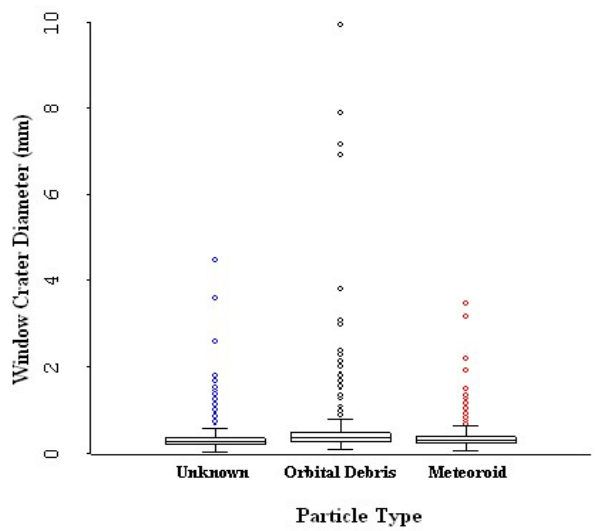

Figure 29   Boxplot of Window Crater Damage conditioned on Particle Type

Although inclination is not a good predictor for total window impacts, it is a good predictor for damage size. Figure 30 below shows that the average damage diameter of window impacts increases with inclination. The average damage diameters can be seen in Table 2. A possible reason for this is that the flight attitude required for specific missions (which can be common for specific inclinations) may require that the windows be pointed in the direction of the velocity vector, exposing them to more debris. For example, the attitude time line for STS-68 indicate that 26.79% of the mission was flown in a nose-forward (into the velocity vector) attitude. A look at window hits for STS-68 indicate that 13 of 14 window hits occur on windows 2, 3, and 4 (the forward center windows).

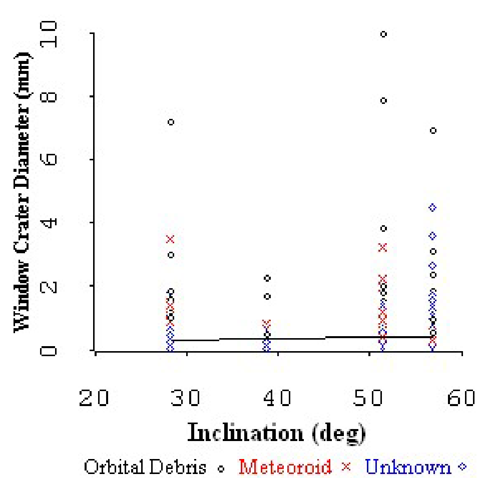

Figure 30   Window Crater Diameter vs. Inclination

Inclination (deg)	Average Damage Diameter (mm)
28.5	0.364
39.0	0.375
51.6	0.412
57.0	0.531

Table 2 Window Crater Diameter vs. Inclination

Window Damage is seen to be consistent across all altitudes flown. So, just as any one altitude is just as likely to receive as many hits as any other altitude, crater size is no different. This is seen below in Figure 31.

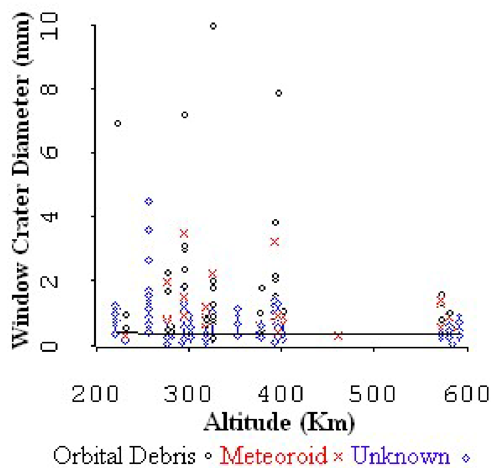

Figure 31 Window Crater Diameter vs. Altitude

Average window crater size appears to be decreasing from 1992 to 2002. A closer look at the residual line in the graph below shows a bend in the data at the year 1997. In 1997 inspectors began using an optical micrometer and fiber optic light source to identify window damage. This new tool allows detection of smaller damage features, which accounts for the decreasing trend seen in Figure 32. [Ref. 1]

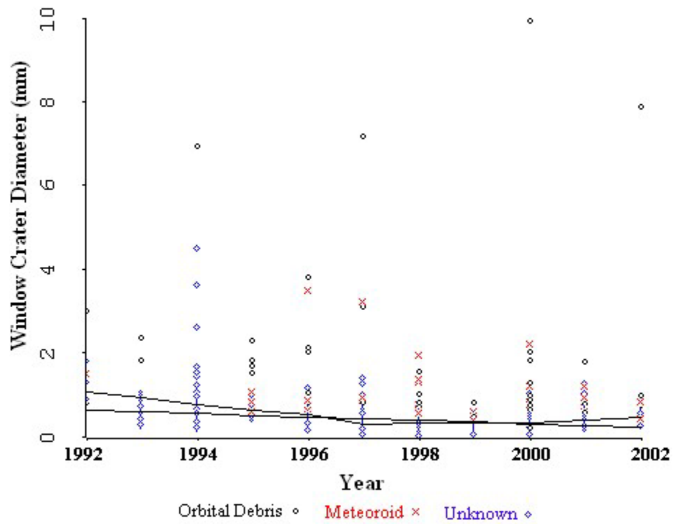

Figure 32 Window Crater Diameter vs. Year

3. Window Replacement

Window replacement is tracked for a variety of reasons. Flight safety analysts look at this for crew safety and safety of flight issues. Comptrollers and logisticians look at this to determine parts replacement timelines and budget requirements for those replacement parts. Figure 33 below shows that windows are replaced at an average of 1.74 windows per mission. This is consistent across the orbiter fleet.

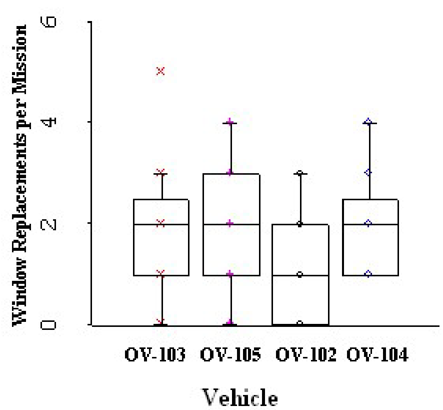

Figure 33 Boxplot of Window Replacements per Mission conditioned on Vehicle

Figure 34 shows a window replacement rate of 0.183 window replacements per mission day for OV-103, OV-104 and OV-105. OV-102 has a 130% lower replacement rate of 0.079 windows replaced per mission day.

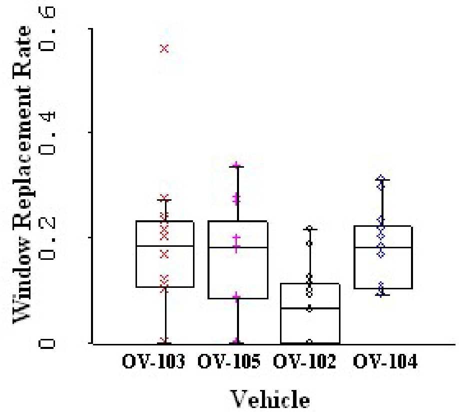

Figure 34 Boxplot of Window Replacement Rate conditioned on Vehicle

Inclination is shown below in Figure 35 to be a good predictor for window replacement rate. As the inclination of the mission orbit increases, the window replacement rate increases. This is best explained by reviewing Figure 30, which shows that window impact crater diameter increases as inclination increases. It makes sense that as damage size increases so does replacement rate.

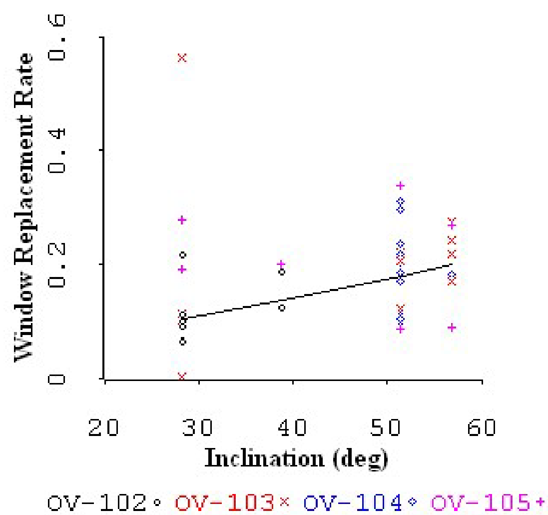

Figure 35 Window Replacement Rate vs. Inclination

Window replacements are shown in Figure 36 to increase with longer duration missions, just as the total number of window impacts increase with longer duration missions.

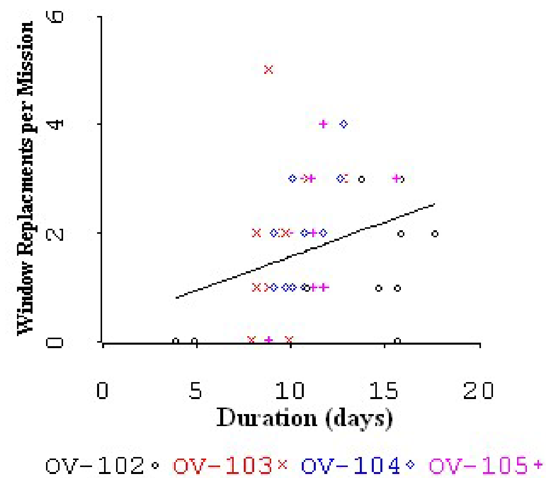

Figure 36 Window Replacements per Mission vs. Duration

To plan for future window replacement costs, Figure 37 shows that the average of 1.74 windows replaced per mission, and the window replacement rate of 0.153 windows replaced per mission day have been consistent from 1992 to 2002.

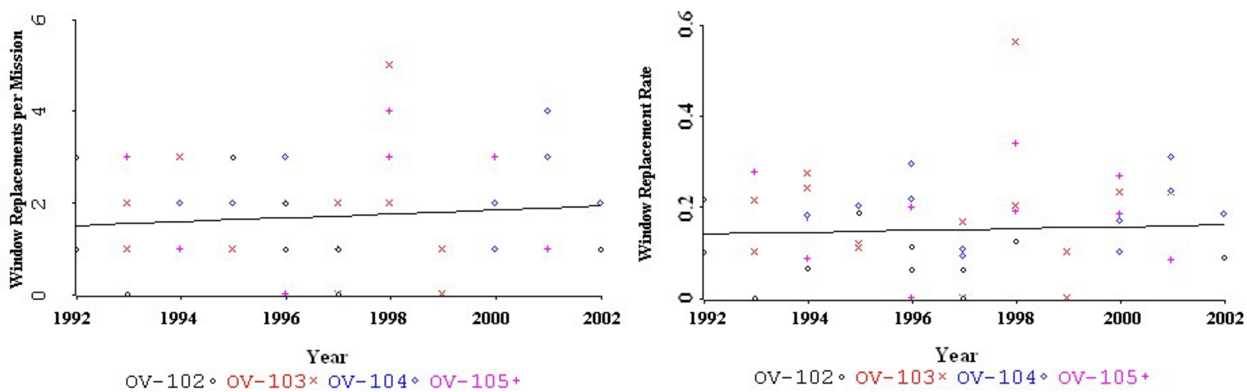

Figure 37 Window Replacements and Replacement Rate vs. Year

D. RADIATOR DATA

Of the 2,067 M/OD impacts cataloged in the Hypervelocity Impact Database, 298 are impacts to the radiators located on the inside of the payload bay doors. These impacts are most interesting because the radiator is the only surface area examined during post-flight inspections that is exposed only while in orbit. Other surfaces inspected are exposed to impacts during launch, landing, and on the ground, as well as while on orbit,

but radiator damage only occurs when the payload bay doors are open on orbit. Figure 3 and Figure 4 in Chapter 1 illustrate the silver-teflon tape and aluminum facesheet, which protect the radiator's honeycomb core and radiator flow tubes.

1. Correlation between Radiator Hits and Mission Parameters

An analysis of radiator hits per mission shows that there is no statistical increase or decrease in the number of radiator impacts per mission or radiator impact rate, given mission inclination, altitude, duration or year. This can be seen graphically in Appendix B. Table 3, below, displays the total number of radiator impacts, average impacts per mission, and average impact rate.

Total Radiator Impacts	Average Radiator Impacts per Mission	Impact Rate (Impacts per Mission Day)
298	5.9	0.556

Table 3 Radiator Impacts

2. Radiator Tape Damage

The payload bay door radiators are covered with a silver-Teflon thermal control tape, which is bonded to the exterior of the radiator's aluminum facesheet. Impacts are cataloged in the database when damage exceeds 1.0 mm in diameter, as seen in Table 1. Figure 38 below shows that of the radiator hits cataloged, damage to the radiator silver-Teflon tape caused by orbital debris is 20% larger than damage caused by Meteoroids.

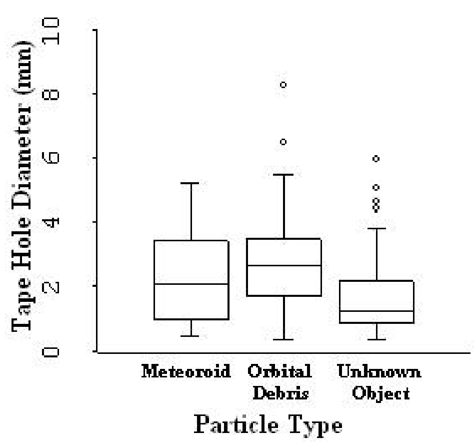

Figure 38 Boxplot of Tape Hole Diameter conditioned on Particle Type

A comparison of tape hole diameter to the mission parameters, indicate that inclination is not a good predictor for damage size. Figure 39, seen below, shows that the average damage diameter of the silver-Teflon tape is statistically the same across all inclinations. The image on the left is a scatterplot of Tape Hole Diameter vs. inclination. The figure on the right is a boxplot of the same data.

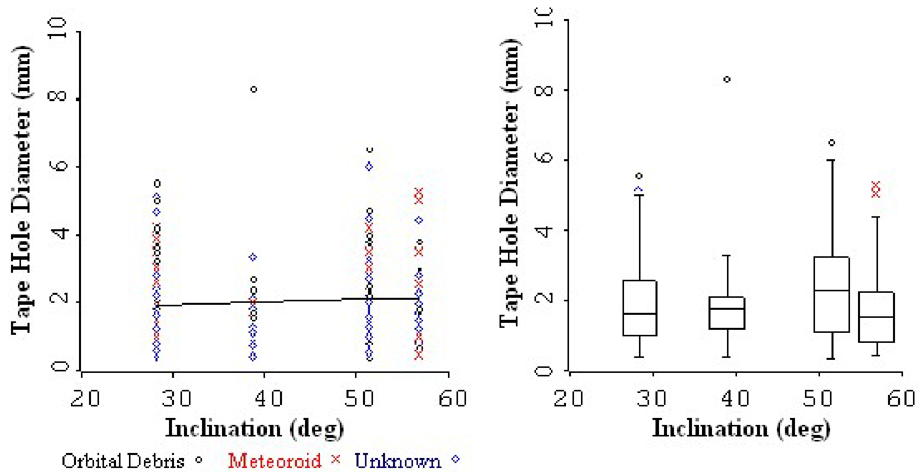

Figure 39 Tape Hole Diameter vs. Inclination

Altitude was seen to be a good predictor for damage diameter in the silver-Teflon tape. Figure 40 below shows a scatterplot on the left and a boxplot on the right. Looking at the regression line on the scatterplot alone, it seems that altitude is not a good predictor for damage size, but a look at the residual line shows something different. The residual line of the scatterplot on the left and the boxplot on the right, with altitude broken into four slices, shows that the average tape hole diameter at altitudes of roughly 300-350 km and altitudes greater than 400 km are 50% higher than other altitudes flown by the space shuttle orbiter. Table 4 below shows the average diameters associated with each of the four sliced altitudes.

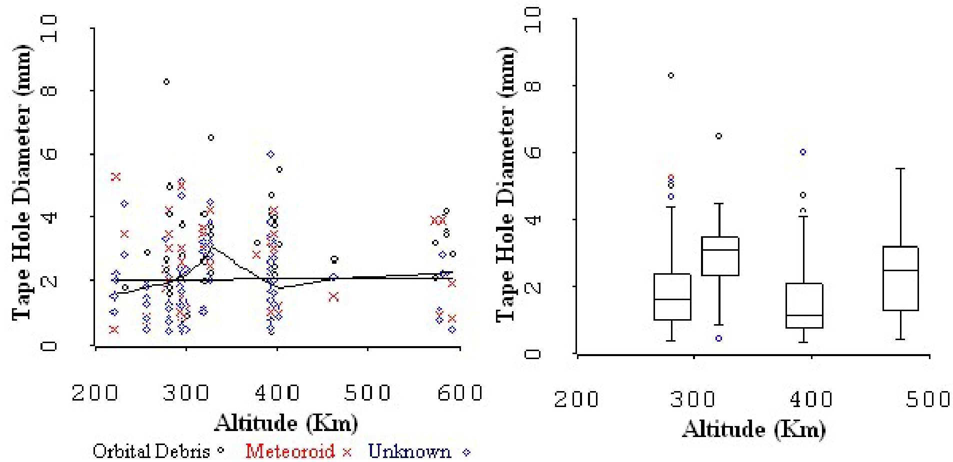

Figure 40 Tape Hole Diameter vs. Altitude

Altitude	200-300 km	300-350 km	350-400 km	> 400 km
Average Tape Hole Diameter (mm)	1.905	2.872	1.603	2.455
Max Tape Hole Diameter (mm)	8.30	6.50	6.00	5.54
Min Tape Hole Diameter (mm)	0.40	0.45	0.38	0.47

Table 4 Average Tape Hole Diameter at given Altitudes

Year was also seen to be a good predictor for damage diameter of the silver-Teflon tape. Figure 41, below, shows a 113% increase in diameter size from 1992 to 2002. There was no curvature to the residual line, so this increase is not following any type of cyclic pattern.

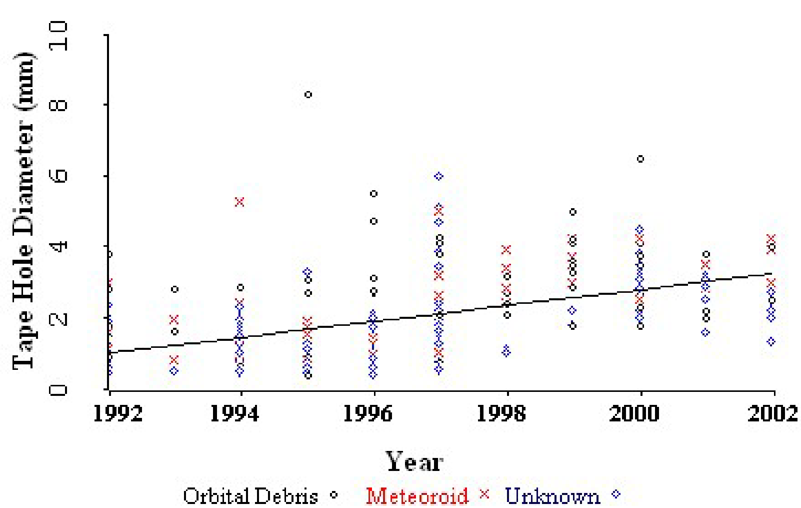

Figure 41 Tape Hole Diameter vs. Year

3. Radiator Facesheet Damage

Of the 298 radiator impacts cataloged in the database, 171 penetrated through the silver-Teflon tape and impacted the aluminum facesheet, 50 of which passed through the facesheet and perforated the honeycomb core. Of these penetrations, 47 were from meteoroids, 57 from orbital debris and 67 from unknown objects. Figure 42 below shows that the average damage diameter caused by orbital debris is 18% greater than damage caused by meteoroids.

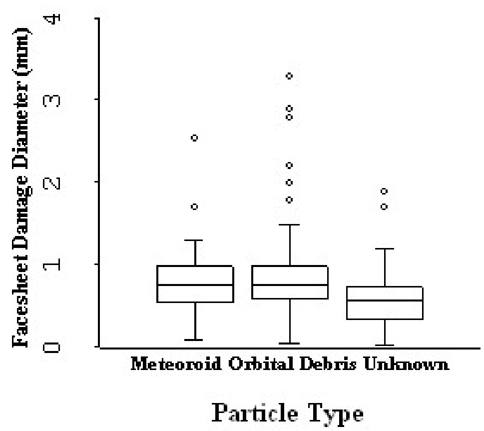

Figure 42 Boxplot of Average Facesheet Damage Diameter conditioned on Particle Type

Altitude was found not to be a good predictor for facesheet damage diameter. Although the regression line in Figure 43, below, seems to be decreasing in diameter with increasing altitude, the slope of the line is statistically zero, and therefore the average facesheet damage diameter is statistically the same across all altitudes flown by the shuttle orbiters.

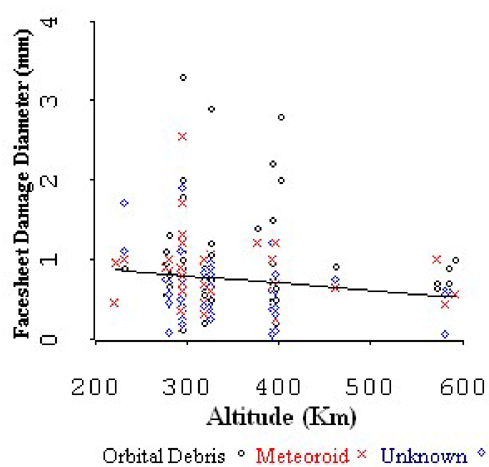

Figure 43 Radiator Facesheet Damage Diameter vs. Altitude

Inclination seems to be a good predictor for facesheet damage diameter. The average damage diameter for 28.5 deg, 39 deg, 51.6 deg, and 57 degree are 0.915 mm, 0.655 mm, 0.659 mm, and 1.054 mm respectively. This is graphically represented below in Figure 44. Of the four inclinations flown, 28.5 deg and 57 deg are 39% and 61% larger, respectively, than 39 deg and 51.6 deg inclinations.

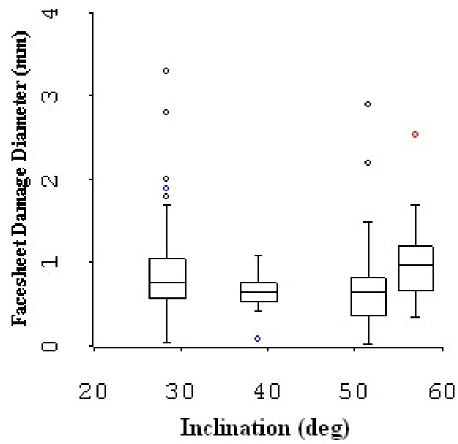

Figure 44 Boxplot of Radiator Facesheet Damage conditioned on Inclination

The average facesheet damage diameter has decreased by 258% between 1992 (1.241 mm) and 2002 (0.346 mm). This is seen graphically in Figure 45 below.

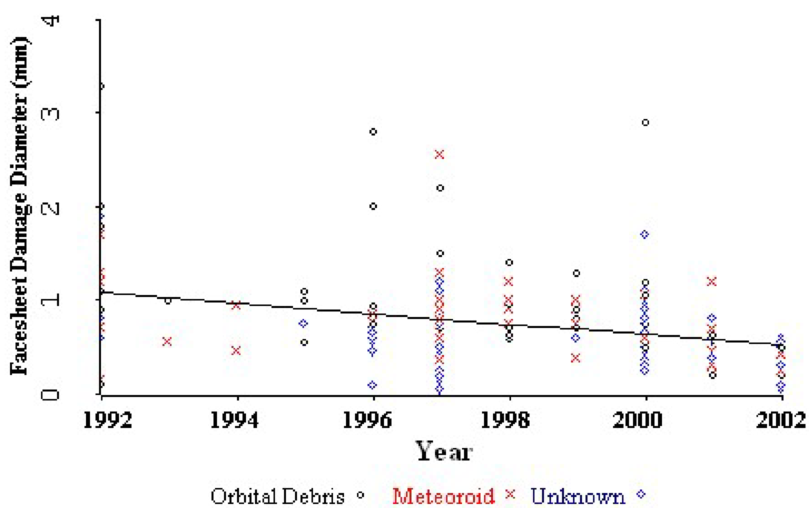

Figure 45 Radiator Facesheet Damage from 1992 to 2002

Of the 171 radiator facesheet penetrations, 50 impactors broke through the facesheet and impacted the honeycomb core. Inclination, altitude and year were all poor predictors for facesheet hole diameter. This can be seen graphically in Appendix B.

4. Facesheet Penetration Rate

The facesheet penetration rate, like radiator hits per mission data, was found to be statistically the same across all inclinations and altitudes flown. From 1992 through 2002, the penetration rate was also found to be statistically the same. This can be seen graphically in Appendix B. Table 5, below, shows the total number of facesheet penetration, facesheet impacts per mission and facesheet impact rate.

	Total	Meteoroid	Orbital Debris	Unknown
Total Radiator Facesheet Penetrations	171	47	57	67
Average Radiator Facesheet Impacts per Mission	3.42	1.58	1.46	2.86
Average Radiator Facesheet Impact Rate (Impacts per Mission Day)	0.3136	0.151	0.142	0.262

Table 5 Radiator Facesheet Penetrations (STS-50 through STS-110)

E. RCC AND FRSI DATA

The Reinforced Carbon-Carbon (RCC) wing leading edge of the Space Shuttle Orbiters' wings and the Flexible Reusable Surface Insulation (FRSI) are also inspected thoroughly during post-flight inspections. 43 RCC impacts and 120 FRSI impacts are cataloged in the database. Detailed descriptions of these surfaces are in Chapter 2.

1. Reinforced Carbon-Carbon (RCC)

Analysis of RCC data in the database show no statistical increasing or decreasing trends in RCC hits per mission when compared to inclination, altitude, duration or year. As well, the hit rate (hits per mission day) shows no increasing or decreasing trends when compared to inclination or altitude. This also can be seen in Appendix B. Interestingly,

though, there is a 220% increase in RCC hit rate from 1992 to 2002, seen graphically below in Figure 46.

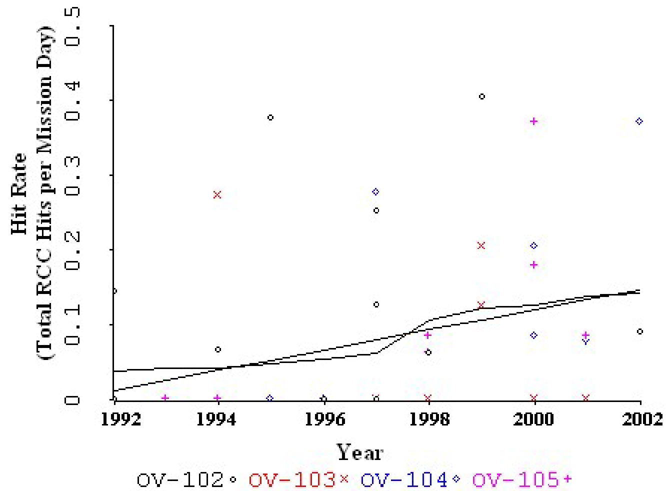

Figure 46   RCC Hit Rate vs. Year

A comparison of Hit Rates by Meteoroids and Orbital Debris is also interesting. Table 6, below, shows that the average hit rate by orbital debris and unknown objects are 640% larger than meteoroids. This comparison can also be seen in Figure 47 and Figure 48. Another interesting find in this comparison is that the orbital debris RCC hit rate increases suddenly in 1997, while the meteoroid RCC hit rate remains consistent. The fact that 93% of RCC hits are from orbital debris and unknown (unidentifiable) objects, suggests that these hits are the result of inner atmosphere impacts during ascent and descent. Although it is plausible that the RCC hit rate could be following the cyclic pattern of the solar cycle, as window data and total impact data suggest, the sudden increase in RCC hit rate in 1997 and lack of meteoroid hits suggests the trends associated with impacts are due to impacts occurring during ascent and descent.

	Total	Meteoroid	Orbital Debris	Unknown
Total RCC Hits	43	3	18	22
Average Hit Rate	0.0801	0.0050	0.0372	0.0378
Min Hits per Mission	0	0	0	0
Max Hits per Misison	6	1	2	6

Table 6   RCC Impact Data

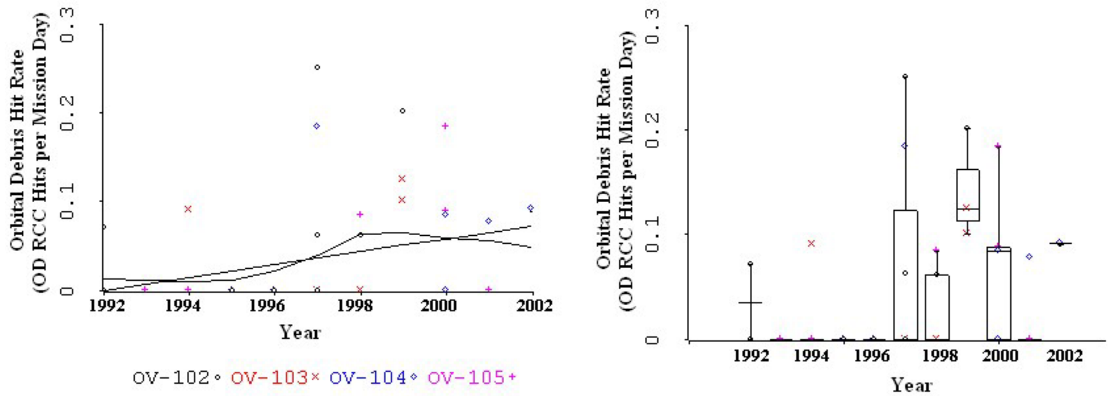

Figure 47 RCC Hit Rate by Orbital Debris vs. Year

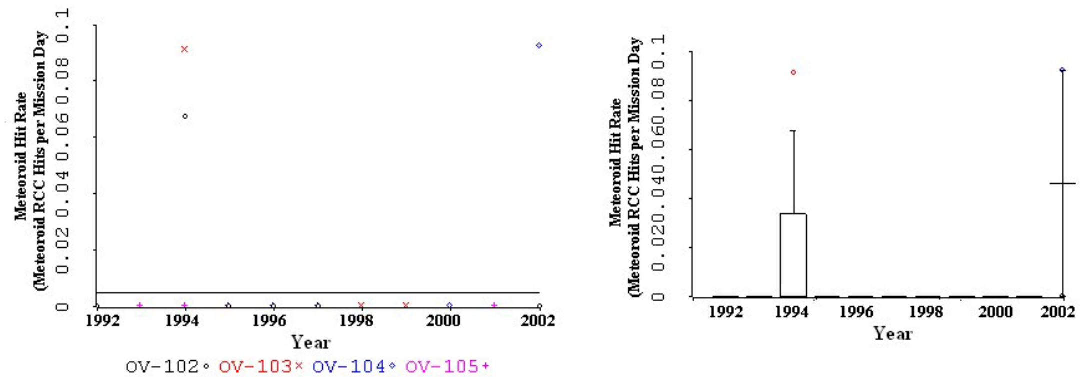

Figure 48 RCC Hit Rate by Meteoroids vs. Year

Damage diameters found during RCC post flight inspections show that orbital debris damage is 12% larger than damage caused by meteoroids. This can be seen in Figure 49 and Table 7, below.

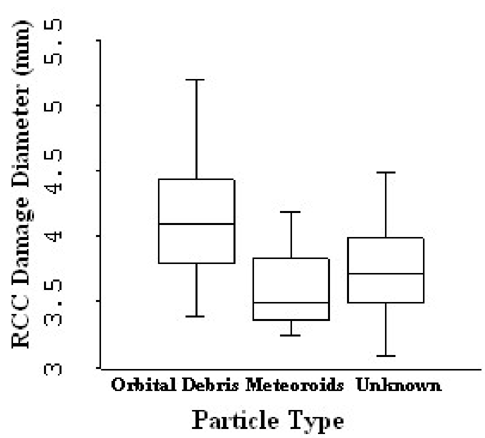

Figure 49 Boxplot of RCC Damage Diameter vs. Particle Type

	Meteoroid	Orbital Debris	Unknown
Average Diameter (mm)	3.65	4.10	3.71
Min Diameter (mm)	3.25	3.40	3.10
Max Diameter (mm)	4.20	5.20	4.50

Table 7 RCC Damage Diameter

Inclination and year were found to be poor predictors for RCC damage diameter, while altitude was found to be a good predictor, showing a 17% increase between lower and higher altitudes. This can be seen graphically below in Figure 50.

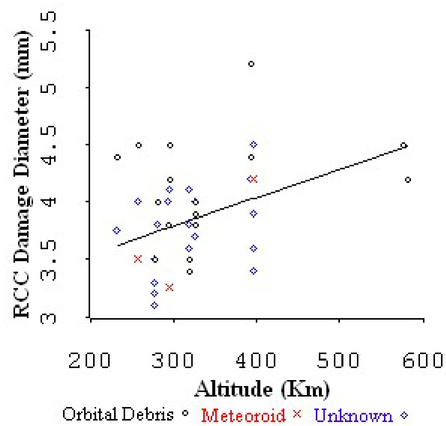

Figure 50 RCC Damage Diameter vs. Altitude

2. Flexible Reusable Surface Insulation (FRSI)

The impact database contains 120 impacts into the FRSI on the outside of the payload bay doors. This surface area was not examined during post-flight inspections until STS-73, in 1995, when a 7 mm x 12 mm diameter hole, with cracks extending in the outer rubber surface of the FRSI, was noticed. 27 of the 33 following missions have FRSI impact damage cataloged in the database.

Analysis of FRSI data in the database show no statistical increasing or decreasing trends in either the FRSI hits per mission or FRSI hit rate when compared to inclination, altitude, or year.

Damage size was found to be statistically the same between meteoroid and orbital debris damage. This can be seen graphically in Figure 51 below. Table 8 also shows this.

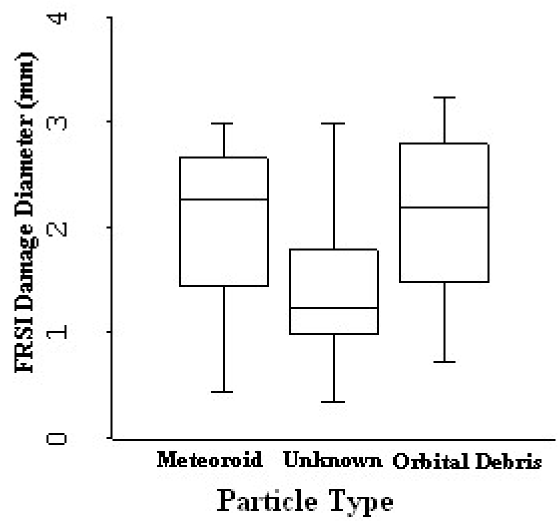

Figure 51 Boxplot of FRSI Damage Diameter vs. Particle Type

	Meteoroid	Orbital Debris	Unknown
Total FRSI Hits	36	41	43
Average Diameter (mm)	2.05	2.16	1.42
Min Diameter (mm)	0.45	0.73	0.35
Max Diameter (mm)	3.00	3.25	3.00

Table 8 FRSI Damage Data

Inclination was found to be a good predictor for damage size. Figure 52 below shows that 51.6-degree inclination provides the largest average damage diameters, followed by 57-degree inclinations. It is interesting that inclination was also a good predictor for radiator facesheet damage, which is on the opposite side of the payload bay door as the FRSI. A comparison these two surface areas with respect to attitude time line data should be conducted in the future. A relational database would make this effort less demanding.

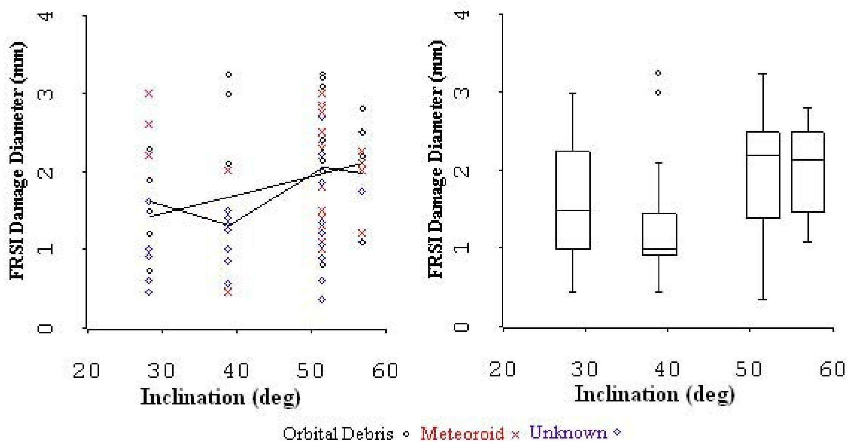

Figure 52 FRSI Damage Diameter vs. Inclination

Altitude was found not to be a good predictor for FRSI damage from all M/OD impactors, but was a good predictor for damage caused by meteoroids. A 43% increase in FRSI damage diameter when caused by meteoroids is seen below in Figure 53.

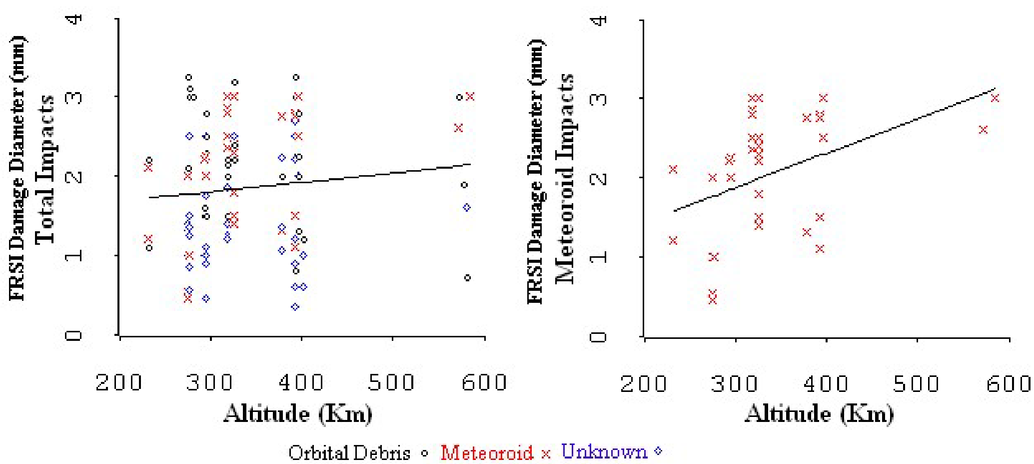

Figure 53 FRSI Damage vs. Altitude

Year was also found to be a good predictor for FRSI damage diameter. The residual line on Figure 54 below indicates an 85% increase in damage size from 1995 to 1999, with a 102% decrease from 1999 to 2002. Interestingly, even though there is no statistical curvature to the residual line in Figure 55, the average hit rate seems to follow the trends of FRSI damage diameter.

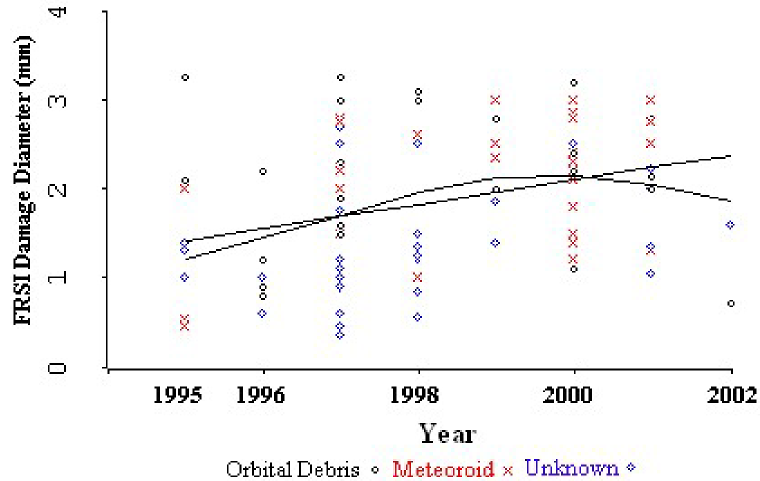

Figure 54 FRSI Damage Diameter from 1995 to 2002

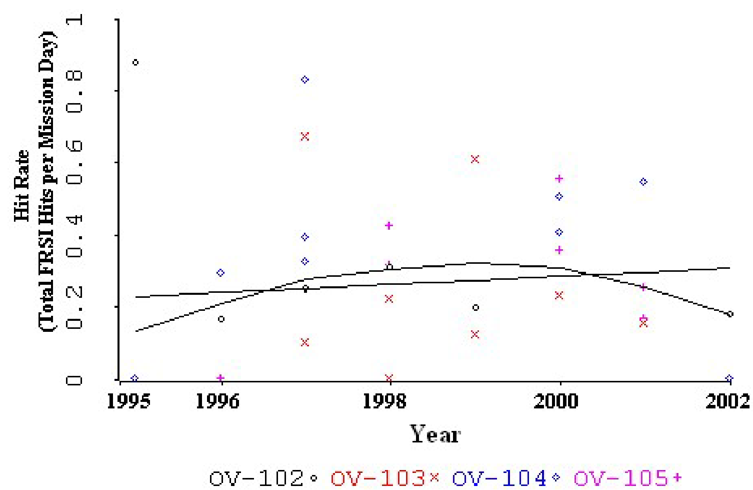

Figure 55 FRSI Hit Rate from 1995 to 2002

F. ORBITER COMPARISON

A comparison of shuttle orbiter vehicles with many of the above mentioned parameters show that damage occurring to the space shuttle is, with few exceptions, consistent across the orbiter fleet. There are five instances where damage to one or more of the orbiter vehicles is different from the rest of the fleet, and one instance where a mission parameter is different.

Of the mission parameters used for analysis (inclination, altitude, duration, year), mission inclinations flown by the orbiters are found to be different. OV-102 flew 11 of

her 13 missions at 28.5-degrees inclination, and OV-104 flew 11 of her 12 missions at 51.6-degrees inclination. Figure 56 and Table 9 illustrates these findings. This is interesting because it gives an idea about the different kinds of missions assigned to the different orbiter vehicles, but also because it is plausible that the differences between inclinations flown by the orbiter vehicles may relate to other differences between them.

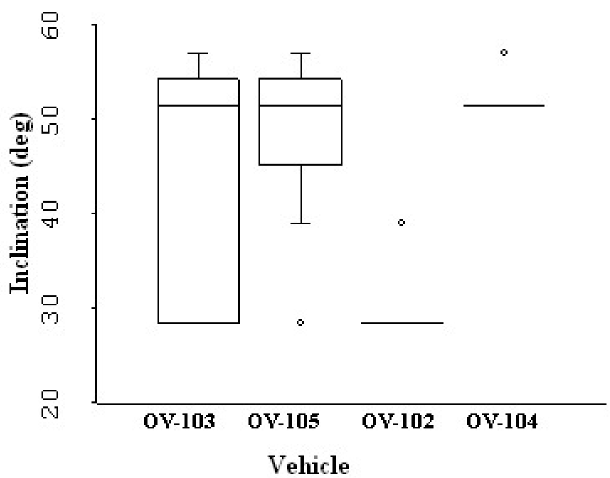

Figure 56 Boxplot of Inclination vs. Vehicle

	OV-103	OV-105	OV-102	OV-104
Total Missions	14	11	13	12
i = 28.5 deg	5	2	11	0
i = 39.0 deg	0	1	2	0
i = 51.6 deg	5	5	0	11
i = 57.0 deg	4	3	0	1

Table 9 Mission Inclinations flown by Shuttle Orbiter Vehicles

Window replacement rate of OV-102 was found to be 130% lower than the rest of the fleet, illustrated in Figure 57.

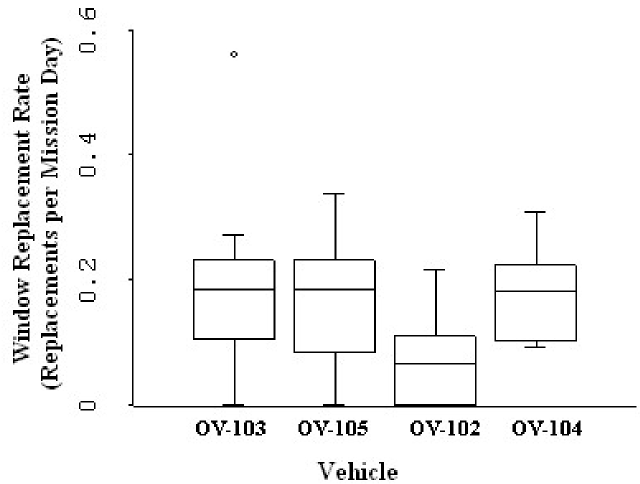

Figure 57 Boxplot of Window Replacement Rate vs. Vehicle

The average window crater diameters found on OV-102 and OV-105 were found to be 24% and 19% lower, respectively, than average window crater diameters found on OV-103 and OV-104. This is illustrated in Figure 58 and Table 10

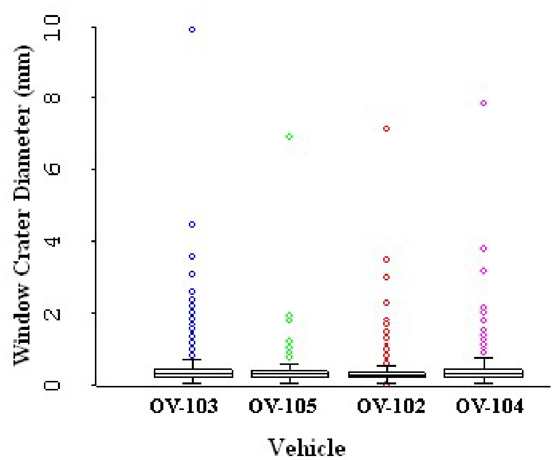

Figure 58 Boxplot of Window Crater Diameter vs. Vehicle

	OV-103	OV-105	OV-102	OV-104
Total cataloged Window Hits	435	326	440	297
Average Window Crater Diameter (mm)	0.435	0.380	0.363	0.455
Minimum Diameter (mm)	0.050	0.071	0.000	0.060
Maximum Diameter (mm)	9.955	6.950	7.180	7.900

Table 10 Window Crater Diameters

OV-104 was found to have the highest radiator impact rate 63%, seen in Figure 59, and the lowest average radiator facesheet damage diameter by 18%, as seen in Figure 60.

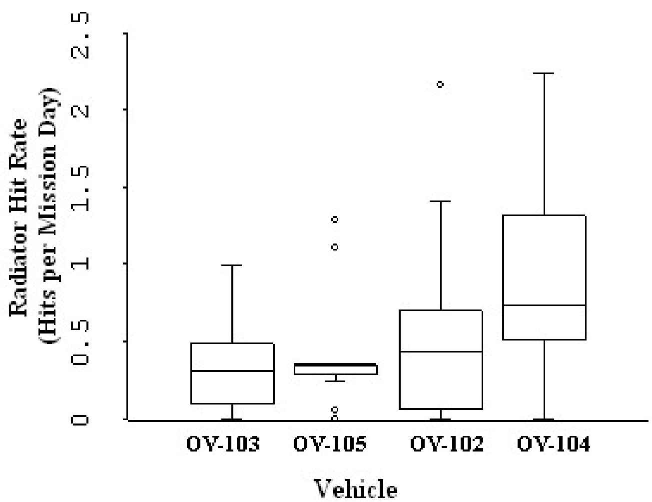

Figure 59 Boxplot of Radiator Hit Rate vs. Vehicle

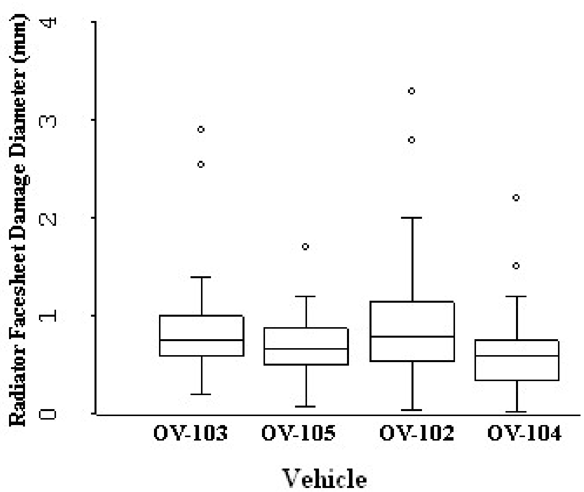

Figure 60 Boxplot of Radiator Facesheet Damage Diameter vs. Vehicle

OV-102 has the lowest FRSI damage diameter by 43%, as seen in Figure 61.

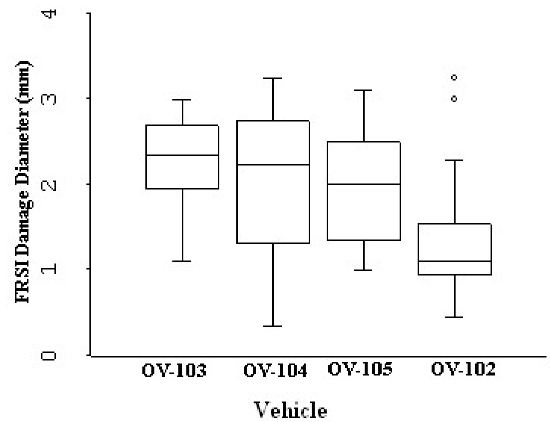

Figure 61 Boxplot of FRSI Damage Diameter vs. Vehicle

These comparison outcomes are the result of many different factors. It seems interesting that OV-102 has the lowest average window crater diameter and lowest window replacement rate, as well as the lowest FRSI average damage diameter, while spending 11 of her 13 missions at 28.5-degrees inclination. Also interesting is the outcome of OV-104 having the highest radiator impact rate with the lowest average facesheet damage diameter while spending 11 of her 12 missions at 51.6-degrees inclination. This could suggest that the amount of debris at 51.6-degrees inclination is greater, but traveling at lower velocities. A better understanding of these outcomes could possibly come from a comparison of this data to the mission time-line attitudes.

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V. CONCLUDING REMARKS

An analysis of NASA's Shuttle Hypervelocity Impact Database, using a statistical regression analysis software package, was conducted to find correlations between Meteoroid and Orbital Debris (M/OD) impacts on the Shuttle Orbiter fleet and specific mission parameters; Inclination, Altitude, Duration and Year. Total M/OD Impact data, regardless of location, particle type or mission was examined first, followed by the subcategories of Window data, Radiator data, Reinforced Carbon-Carbon (RCC) data, and Flexible Reusable Surface Insulation (FRSI) data.

A. TOTAL M/OD IMPACT DATA

Examination of 2067 cataloged M/OD impacts on the shuttle orbiter fleet, regardless of location, particle type, or mission, found that inclination and altitude were not good predictors for M/OD impacts, and that mission duration and year were good predictors for M/OD impacts. The number of total M/OD impacts per mission was found to increase with longer missions and a total M/OD hit rate was found to be 3.71 M/OD impacts per mission day.

The Solar Cycle is seen to have a direct impact on the damage caused to the shuttle orbiter fleet. The data shows a 43% increase in total impacts from 1992 – 2002, but more interestingly, a 298% increase in M/OD hits from 1992 – 1998 and a 177% decrease from 1998 – 2002. A comparison of total M/OD impacts per mission vs. year to the solar cycle indicates that the debris environment (that which is hitting the orbiter fleet) follows the cyclic nature of the solar cycle, with the debris cycle maximum lagging the solar cycle's minimums by a period of about 2 years. Knowledge of this validates the 1997 decision to augment the shuttle orbiter's radiators and wing leading edge RCC to account for increased M/OD impacts.

The 43% increasing trend is due to fact that the database only contains data through part of one solar cycle, from solar minimum to solar maximum. Because of this, the database is incomplete, and requires a minimum of three more years of data in order

to see the effects of one complete solar cycle on the orbiter fleet. For a proper look at the effects of a cyclic pattern on an event, data should be collected and analyzed over several repetitions of that cycle. As more data is cataloged throughout the rest of the current solar cycle (to solar minimum), and through several more cycles, the increasing trend seen in this data will level out.

B. WINDOW DATA

Of the 2,067 cataloged M/OD impacts in the Hypervelocity Impact Database, 1,578 are window impacts; 250 are from meteoroids, 268 from orbital debris and 1,060 are from unknown objects. Examination of these impacts, regardless of location, particle type, or mission, found that inclination and altitude were not good predictors for M/OD window impacts, although mission duration and year were good predictors for M/OD window impacts. The number of total M/OD window impacts per mission was found to increase with longer missions and a total M/OD window impact rate was found to be 2.83 M/OD window impacts per mission day. Meteoroid and orbital debris impact rates are 0.43 and 0.45 impacts per mission day, respectively.

A look at window impacts over the lifetime of the database show a cyclic pattern similar to that found for total M/OD impacts. There is a 2389% increase in the M/OD window impact rate from 1992 to 1998, and a 207% decrease from 1998 to 2002. Meteoroid and orbital debris impact rates on orbiter windows increased 2983% and 1497% respectively from 1992-1998, and decreased 141% and 146% respectively from 1998 to 2002.

Analysis of window damage size indicates that the average window crater diameters caused by orbital debris are 51% larger than those caused by meteoroids. Damage size is seen to increase with inclination, and also shows a decreasing trend from 1992 to 2002.

Window replacement rate is 0.183 windows replaced per mission day for all orbiters, except OV-102, which has a 130% lower window replacement rate of 0.079 windows replaced per mission day. Inclination was found to be a good predictor for

window replacement rate. This makes sense, because as damage size increases with inclination, so should window replacement rate. A look at window replacements for the entire fleet show that a window replacement rate of 0.153 windows replaced per mission day has been consistent from 1992 to 2002.

C. RADIATOR DATA

Of the 2,067 M/OD impacts cataloged in the database, 298 are impacts to the radiators located on the inside of the payload bay doors. These impacts are most interesting because the radiator is the only surface area examined during post-flight inspections that is exposed only while in orbit, and therefore the only surface that receives damage only while in orbit.

Analysis of radiator impacts per mission shows that there is no statistical increase or decrease in the number of radiator impacts per mission or radiator impact rate (impacts per mission day), given mission inclination, altitude, duration or year. The radiator data indicates the orbiter fleet has received an average of 5.9 radiator impacts per mission, and an impact rate of 0.556 radiator impacts per mission day.

Of the radiator hits cataloged, damage to the radiator silver-Teflon tape caused by orbital debris is 20% larger than damage caused by Meteoroids. A comparison of tape hole diameter to the mission parameters indicates that inclination is not a good predictor for damage size, while altitude was seen to be a good predictor for damage diameter in the silver-Teflon tape. The average tape hole diameter at altitudes of roughly 300-350 km and altitudes greater than 400 km are 50% higher than other altitudes flown by the space shuttle orbiter. Year was also seen to be a good predictor for damage diameter of the silver-Teflon tape, as there is a 113% increase in diameter size from 1992 to 2002. No statistical curvature is seen in the residual line, so this increase is not following any type of cyclic pattern.

Of the 298 radiator impacts cataloged in the database, 171 penetrated through the silver-Teflon tape and impacted the aluminum facesheet, 50 of which passed through the facesheet and perforated the honeycomb core. Of these penetrations, 47 were from

meteoroids, 57 from orbital debris and 67 from unknown objects. Data indicates that the average damage diameter caused by orbital debris is 18% greater than damage caused by meteoroids.

Opposite of what was found for damage to the silver-Teflon tape, altitude was found not to be a good predictor for facesheet damage diameter, while inclination was found to be a good predictor for facesheet damage diameter. Of the four inclinations flown, 28.5 deg and 57 deg are 39% and 61% larger, respectively, than 39 deg and 51.6 deg inclinations. Year was also found to be a good predictor for damage size, as the average facesheet damage diameter decreased by 258% between 1992 and 2002.

The facesheet penetration rate, defined as impacts per mission day that break through the silver-Teflon tape and penetrate the aluminum facesheet, was found, similar to radiator hits per mission data, to be statistically the same across all inclinations and altitudes flown. From 1992 through 2002, the penetration rate was also found to be statistically the same.

D. RCC AND FRSI DATA

The Reinforced Carbon-Carbon (RCC) and Flexible Reusable Surface Insulation (FRSI) impacts represent 43 and 120 impacts, respectively, cataloged in the database.

No statistical increasing or decreasing trends are seen in RCC impacts per mission when compared to inclination, altitude, duration or year. As well, the impact rate (impacts per mission day) shows no increasing or decreasing trends when compared to inclination or altitude. There is, though, a 220% increase in RCC impact rate from 1992 to 2002.

The average RCC hit rate by orbital debris and unknown objects are 640% larger than meteoroids. Interestingly, the orbital debris hit rate increases suddenly in 1997, while the meteoroid RCC hit rate remains consistent. Given this and the fact that 93% of RCC hits are from orbital debris and unknown (unidentifiable) objects, it is most likely that these hits are the result of inner atmosphere impacts during ascent and descent. Although it is plausible that the RCC hit rate could be following the cyclic pattern of the

solar cycle, as window data and total impact data suggest, the sudden increase in RCC hit rate in 1997 and lack of meteoroid hits suggests the trends associated with impacts are due to impacts occurring during ascent and descent.

Damage diameters found during RCC post flight inspections show that orbital debris damage is 12% larger than damage caused by meteoroids. Inclination and year were found to be poor predictors for RCC damage diameter, while altitude was found to be a good predictor, showing a 17% increase from lower to higher altitudes.

Analysis of FRSI data in the database show no statistical increasing or decreasing trends in either the FRSI hits per mission or FRSI hit rate when compared to inclination, altitude, or year. Damage size was found to be statistically the same between meteoroid and orbital debris damage.

Inclination was found to be a good predictor for FRSI damage size, as 51.6-degree inclinations provide the largest average damage diameters, followed by 57-degree inclinations. Altitude was found not to be a good predictor for FRSI damage from all M/OD impactors, but was a good predictor for damage solely caused by meteoroids. Data indicates a 43% increase in FRSI damage diameter caused by meteoroids between the lower and higher altitudes. Year was also found to be a good predictor for FRSI damage diameter. There is an 85% increase in damage size from 1995 to 1999, and a 102% decrease from 1999 to 2002.

E. ORBITER COMPARISON

A comparison of shuttle orbiter vehicles show that damage occurring to the space shuttle is, with few exceptions, consistent across the orbiter fleet. Data indicates that OV-105 and OV-102 have 19% and 24% lower average window crater diameters, respectively, than average window crater diameters found on OV-103 and OV-104, and that OV-102 has a 130% lower window replacement rate than the rest of the orbiter fleet. OV-102 also has the lowest FRSI damage diameter by 43%. OV-104 was found to have the highest radiator impact rate 63%, with the lowest average radiator facesheet damage diameter by 18%. These figures are interesting, knowing that OV-102 spent 11 of her 13

missions at 28.5-degrees inclination and that OV-104 spent 11 of her 12 missions at 51.6-degrees inclination.

The most significant of these findings is the knowledge that debris impacting the orbiter fleet follows the cyclic nature of the solar cycle. This allows mission planners and engineers to account for the debris environment while planning future missions, as well as plan for future M/OD upgrades to the orbiter fleet and future spacecraft designs. Also significant is the result of mission parameters on M/OD impacts. It seems obvious that the number of impacts increase with longer missions. Not so obvious, though, was the finding that increased inclination resulted in increased average window damage diameters and window replacement rates, increased average radiator facesheet damage diameters, and increased FRSI damage diameter.

VI. FUTURE RESEARCH

Meteoroid and orbital debris damage to the shuttle orbiter fleet is a fascinating study and has much room for future research. Below are areas for continuing work.

- The Hypervelocity Impact Database has grown large enough that the data should be transferred from it its current form, a MS Excel spreadsheet, to a relational database. Currently, there is no structure that allows for a query of the data. Desired retrieval of information about the data that is not pre-programmed into the spreadsheet is time and labor intensive. A relational database will allow for a variety of data query outside of the few pre-programmed queries that currently exist, and will also permit easier database update and reduced information duplication.
- The data hints that there is a correlation between shuttle orbiter flight attitude and M/OD damage. Attitude timelines for each mission should be incorporated into the hypervelocity impact database and compared to cataloged M/OD damage. M/OD damage compared to common flight attitudes should reveal much information about the impact of specific attitudes chosen for orbiter flight. Likewise, a comparison of damage to the radiator facesheet and to the FRSI, with respect to the flight attitude (as they are on opposite sides of the payload bay door) should also reveal much about the impact of specific attitudes chosen for orbiter flight. A relational database would make this process much easier than in the databases current form.
- The hypervelocity impact database is not complete, due to the fact that its cataloged data spans only part of one solar cycle. The effort of M/OD post-flight survey and hypervelocity impact research must continue to gain a better appreciation of the LEO environment and its impact upon the shuttle orbiter vehicles. The comparison of shuttle orbiter M/OD impact damage to mission parameters should be conducted after another five years of M/OD damage has been cataloged, to show the effects of a complete solar cycle on the hypervelocity impact database.

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VII. APPENDIX A MISSION PARAMETERS

Mission	Vehicle	year	duration (days)	altitude (km)	inclination (deg)
STS-50	OV-102	1992	13.8	**296**	28.5
STS-51	OV-103	1993	9.8	**296**	28.5
STS-52	OV-102	1992	9.9	**302**	28.5
STS-55	OV-102	1993	10.0	**302**	28.5
STS-56	OV-103	1993	9.3	**296**	57.0
STS-59	OV-105	1994	11.2	**224**	57.0
STS-60	OV-103	1994	8.3	**354**	57.0
STS-61	OV-105	1993	10.8	**594**	28.5
STS-63	OV-103	1995	8.3	**394**	51.6
STS-64	OV-103	1994	11.0	**259**	57.0
STS-65	OV-102	1994	14.7	**296**	28.5
STS-66	OV-104	1994	10.9	**304**	57.0
STS-68	OV-105	1994	11.2	**222**	57.0
STS-70	OV-103	1995	8.9	**296**	28.5
STS-71	OV-104	1995	9.8	**394**	51.6
STS-72	OV-105	1996	8.9	**463**	28.5
STS-73	OV-102	1995	15.9	**278**	39.0
STS-75	OV-102	1996	15.7	**296**	28.5
STS-76	OV-104	1996	9.2	**394**	51.6
STS-77	OV-105	1996	10.0	**283**	39.0
STS-79	OV-104	1996	10.1	**394**	51.6
STS-80	OV-102	1996	17.7	**404**	28.5
STS-81	OV-104	1997	10.2	**394**	51.6
STS-82	OV-103	1997	10.0	**580**	28.5
STS-83	OV-102	1997	4.0	**296**	28.5
STS-84	OV-104	1997	9.2	**394**	51.6
STS-85	OV-103	1997	11.9	**296**	57.0
STS-86	OV-104	1997	10.8	**394**	51.6
STS-87	OV-102	1997	15.7	**295**	28.5
STS-88	OV-105	1998	11.8	**320**	51.6
STS-89	OV-105	1998	15.7	**278**	51.6
STS-90	OV-102	1998	15.9	**278**	39.0
STS-91	OV-103	1998	9.8	**378**	51.6
STS-92	OV-103	2000	12.9	**328**	51.6
STS-93	OV-102	1999	5.0	**283**	28.5
STS-94	OV-102	1997	15.7	**296**	28.5
STS-95	OV-103	1998	8.9	**574**	28.5
STS-96	OV-103	1999	9.8	**320**	51.6
STS-97	OV-105	2000	10.8	**328**	51.6
STS-98	OV-104	2001	12.9	**398**	51.6
STS-99	OV-105	2000	11.2	**233**	57.0
STS-100	OV-105	2001	11.9	**398**	51.6
STS-101	OV-104	2000	9.8	**320**	51.6
STS-102	OV-103	2001	12.8	**320**	51.6
STS-103	OV-103	1999	8.0	**587**	28.5
STS-104	OV-104	2001	12.7	**380**	51.6
STS-106	OV-104	2000	11.8	**328**	51.6
STS-108	OV-105	2001	11.8	**398**	51.6
STS-109	OV-102	2002	10.9	**583**	28.5
STS-110	OV-104	2002	10.8	**398**	51.6

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VIII. APPENDIX B MISCELANEOUS GRAPHS

A. TOTAL M/OD IMPACT DATA

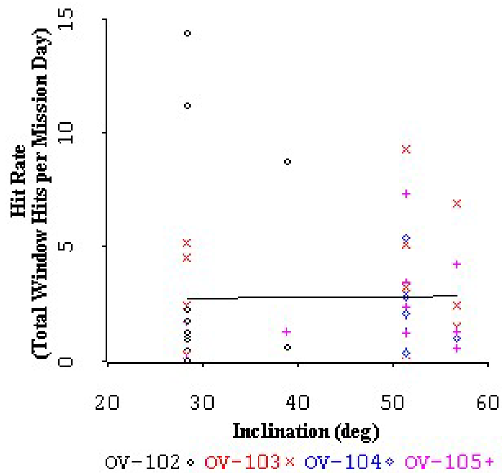

Figure 62 Window Hit Rate vs. Inclination

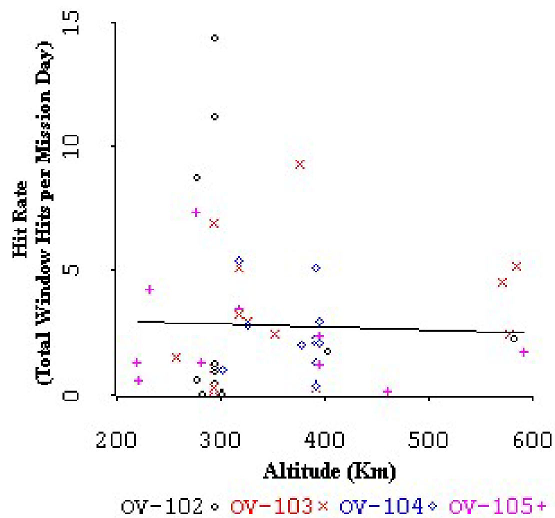

Figure 63 Window Hit Rate vs. Altitude

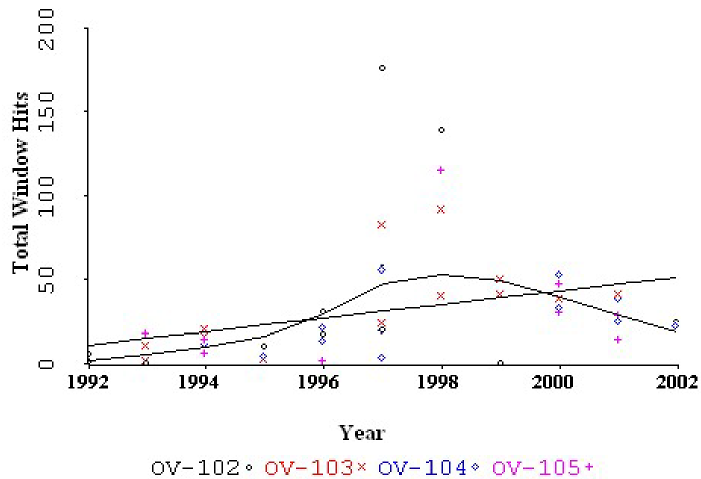

Figure 64 Total Window Hits between 1992 and 2002

B. WINDOW DATA

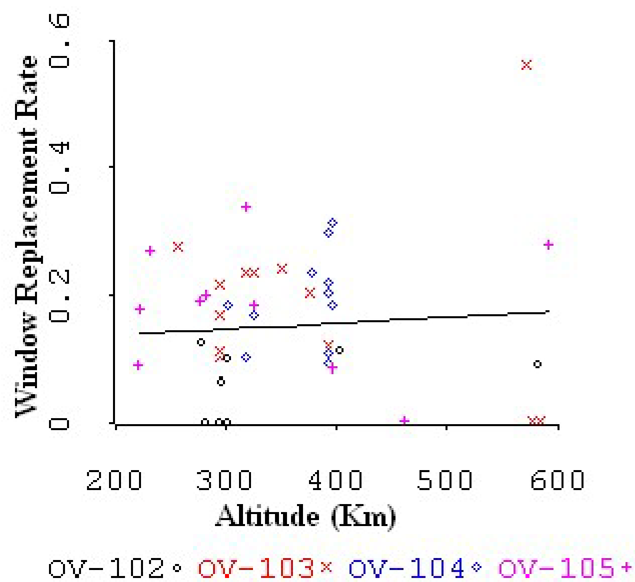

Figure 65 Window Replacement Rate vs. Altitude

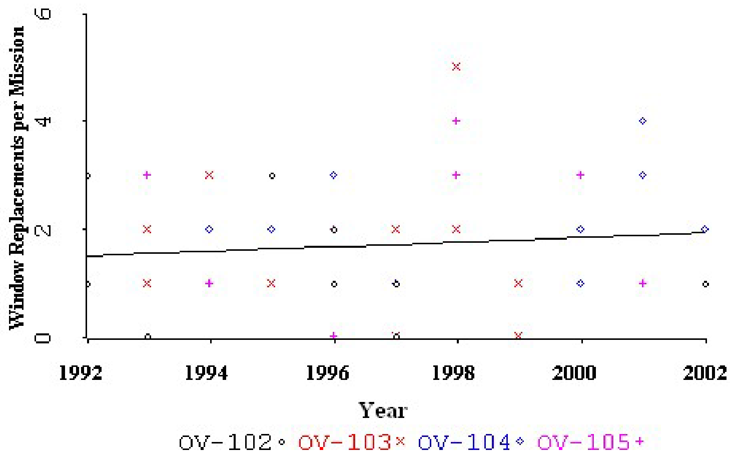

Figure 66 Window Replacements per mission vs. Year

C. RADIATOR DATA

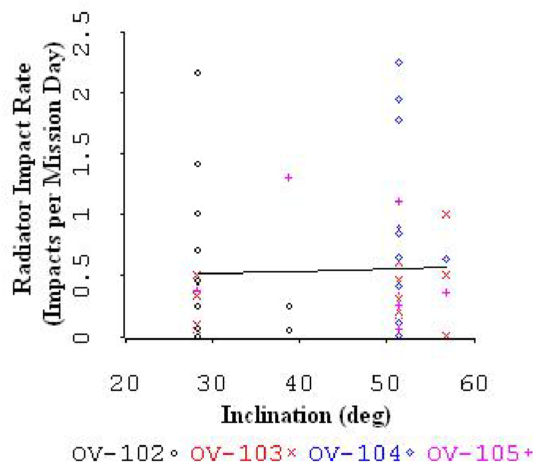

Figure 67 Radiator Impact Rate vs. Inclination

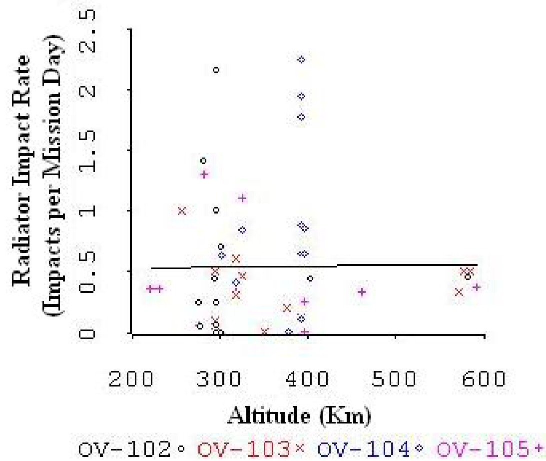

Figure 68 Radiator Impact Rate vs. Altitude

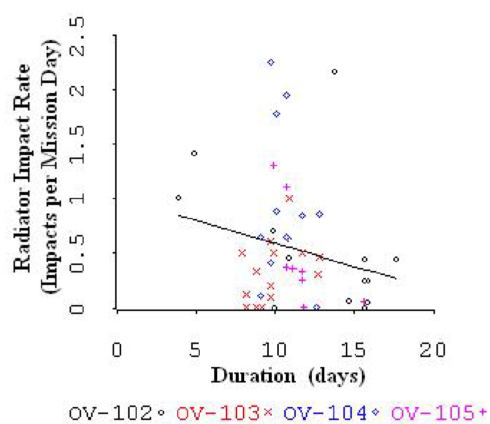

Figure 69 Radiator Impact Rate vs. Duration

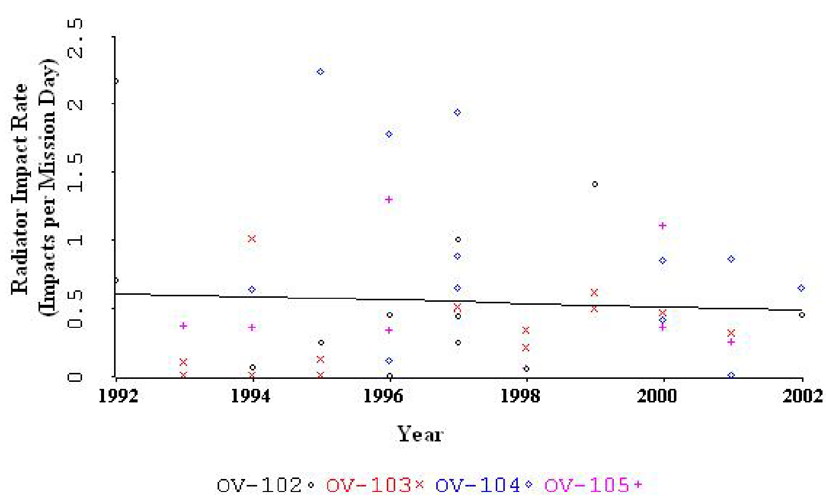

Figure 70 Radiator Impact Rate vs. Year

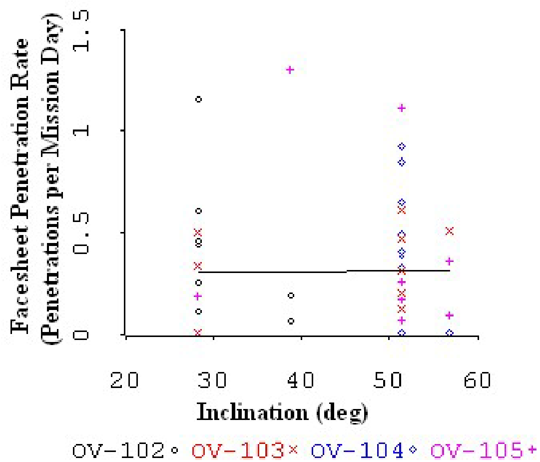

Figure 71 Facesheet Penetration Rate vs. Inclination

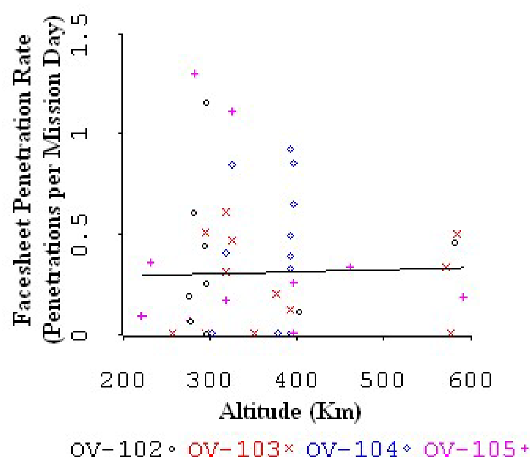

Figure 72 Facesheet Penetration Rate vs. Altitude

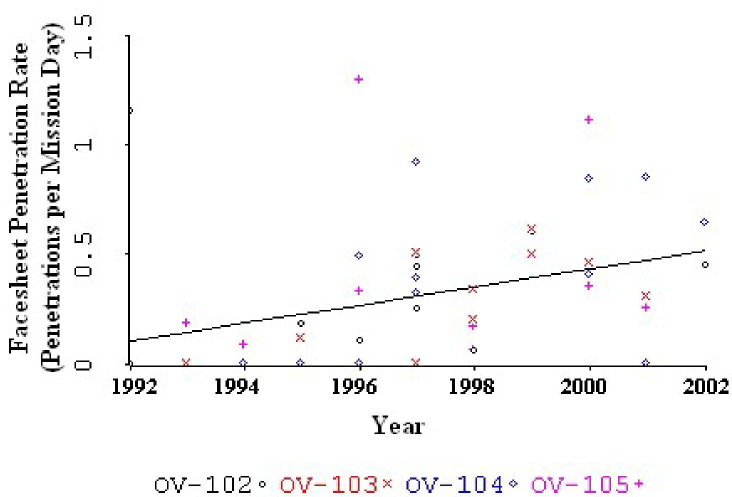

Figure 73 Facesheet Penetration Rate from 1992 to 2002

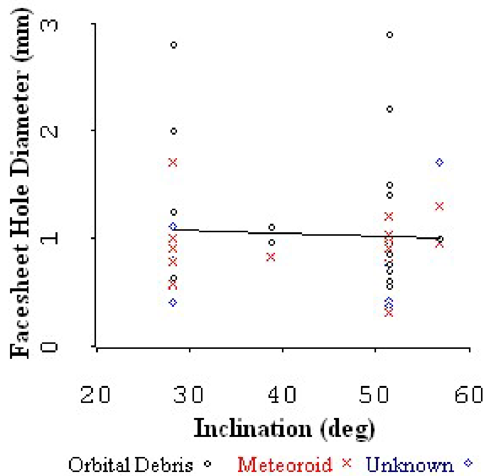

Figure 74 Facesheet Hole Diameter vs. Inclination

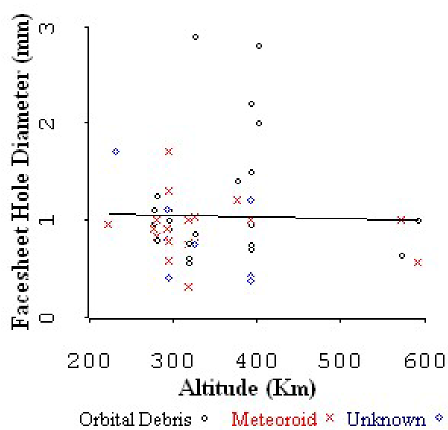

Figure 75 Facesheet Hole Diameter vs. Altitude

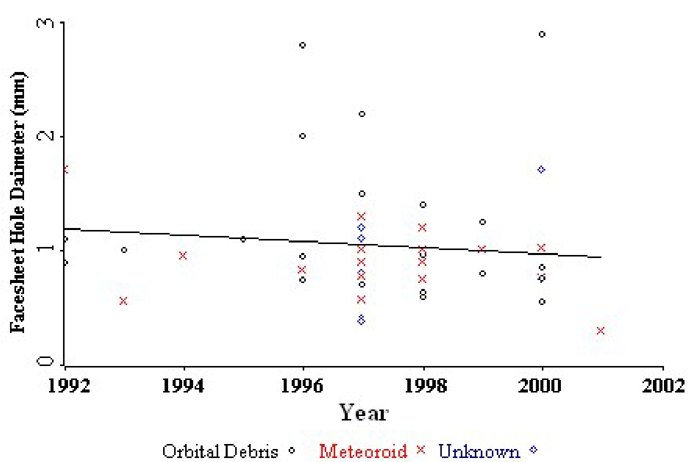

Figure 76 Facesheet Hole Diameter from 1992 to 2002

D. RCC DATA

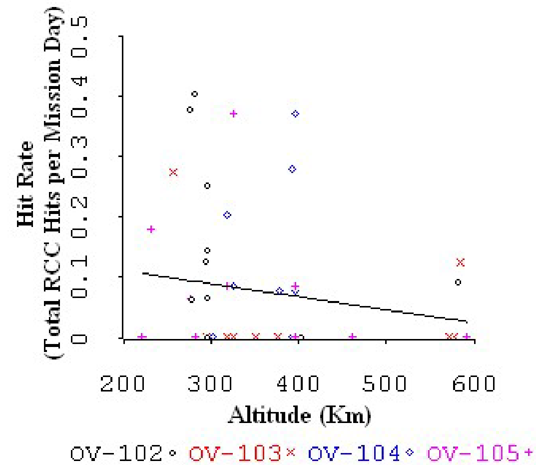

Figure 77 Total RCC Hit Rate vs. Altitude

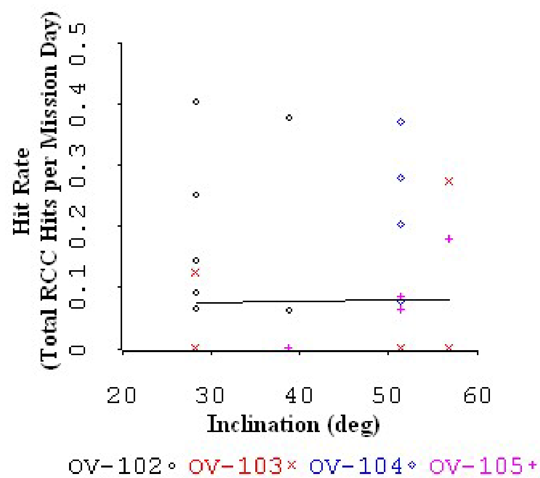

Figure 78 RCC Hit Rate vs. Inclination

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